Is the Universe OUT OF TUNE?

Like the discord of key in
in a skillful orchestra quietly playi
mysterious discrepancies have ari
and observations of the "n
cosmic microwave bac
Either the measurements
or the universe is stranger th

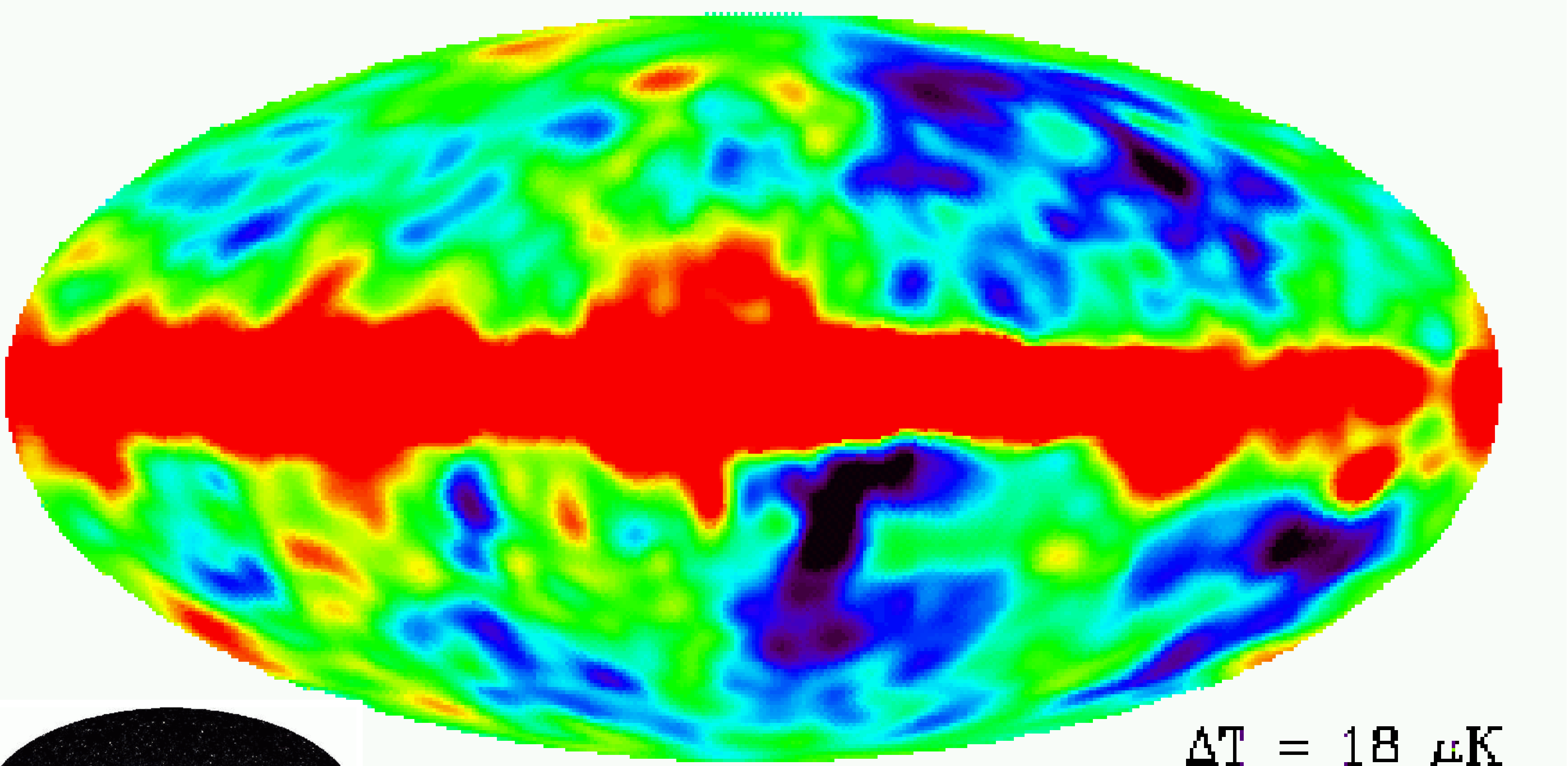
By Glenn D. Starkma
Dominik J. Schwa

If the CMB is right, it is inconsistent with concordance cosmology

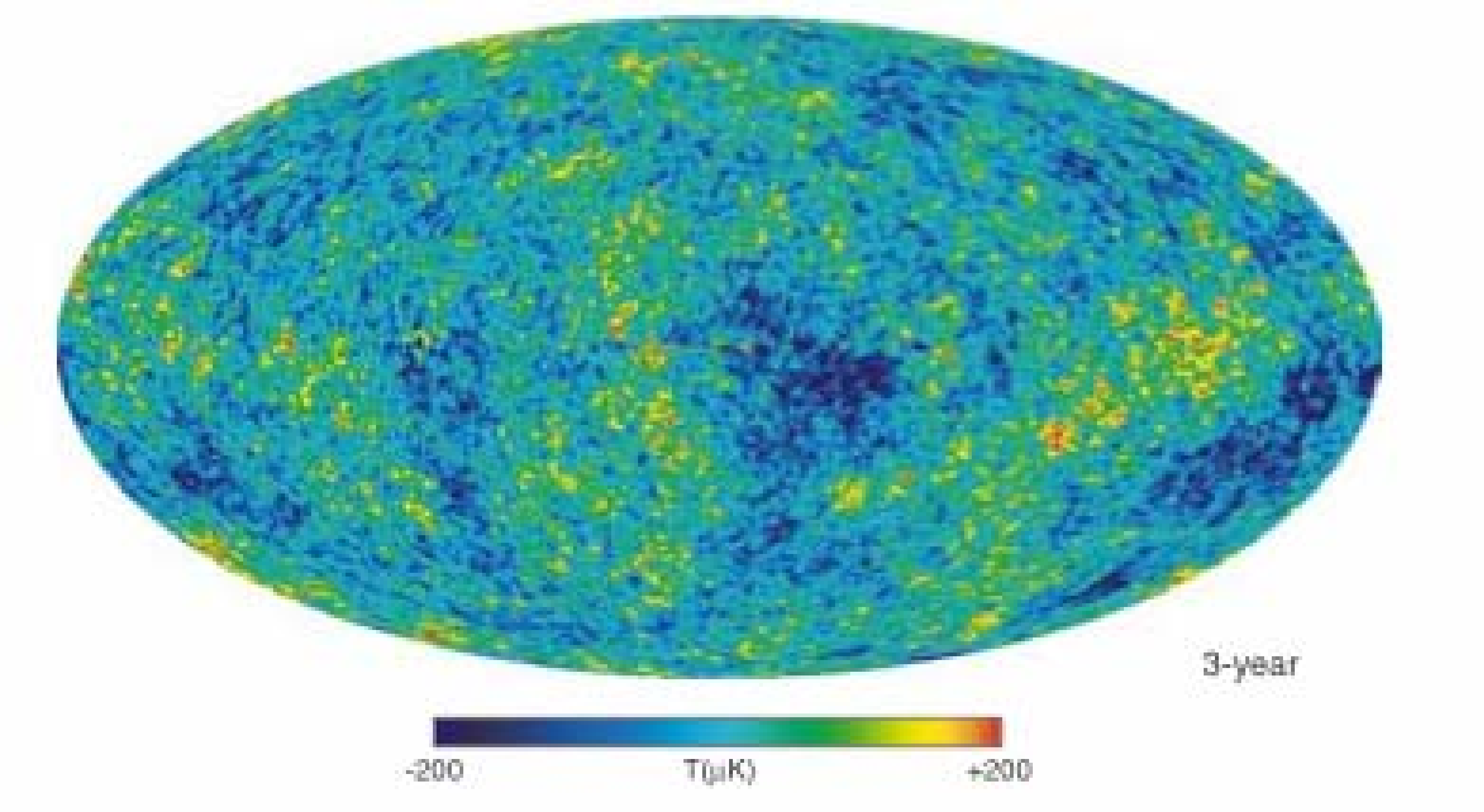
Glenn D. Starkman

Craig Copi, Dragan Huterer & Dominik Schwarz
Neil Cornish, David Spergel, & Eiichiro Komatsu;
Jean-Philippe Uzan, Alain Riazuelo, Jeff Weeks,
Sam Leach, R. Trotta, Ben Wandel
Bob Nichols, Peter Freeman
Kaiki Inoue, Joe Silk, Andrew Jaffe, Anastasiat

COBE - DMR

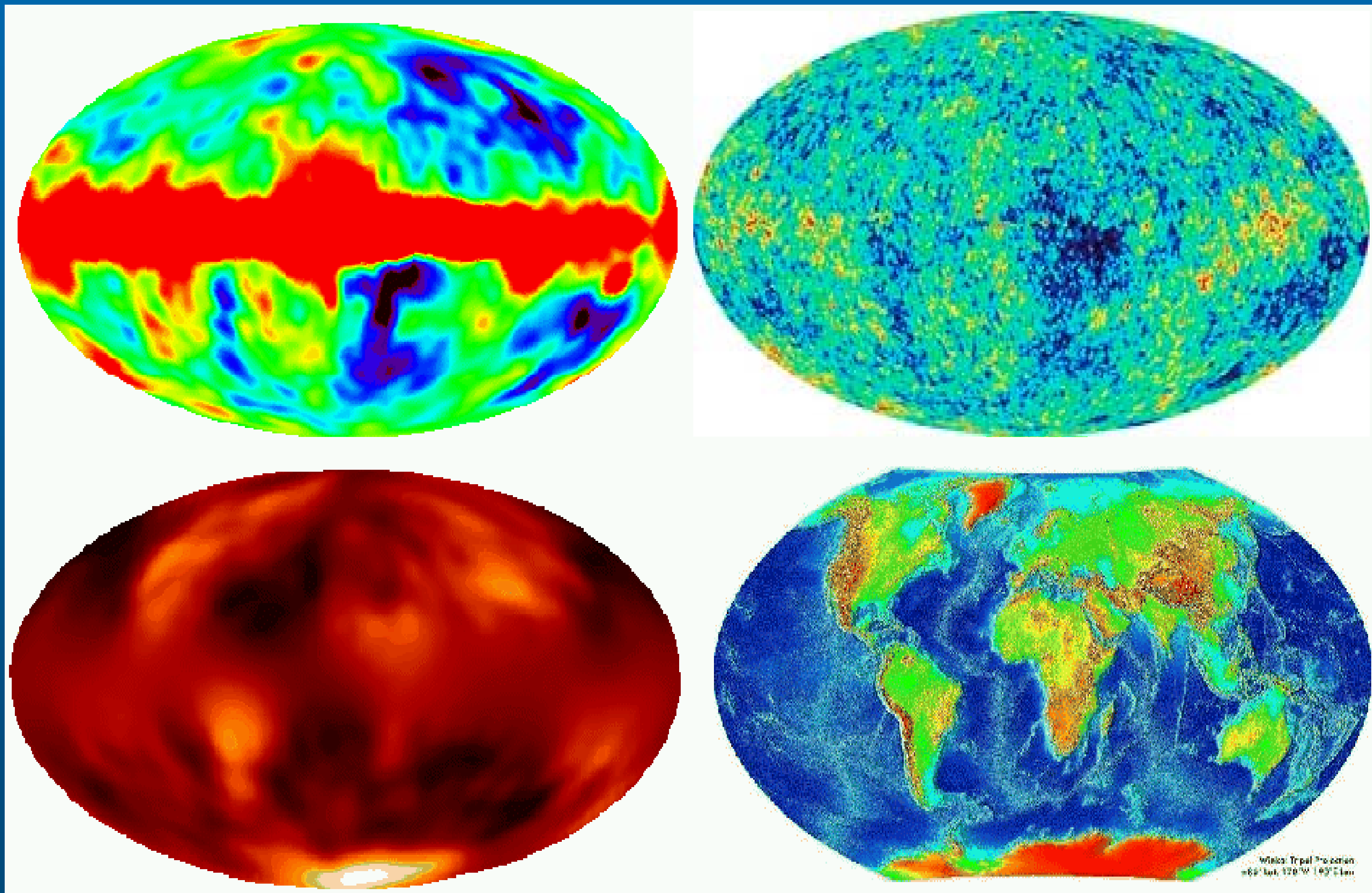


The WMAP Sky



NASA/WMAP Science team

COBE vs. WMAP



Outline

Largest scale properties of the universe:

- Curvature
- Topology

The low-ℓ / large-angle problem

- from C_ℓ to $C(\theta)$

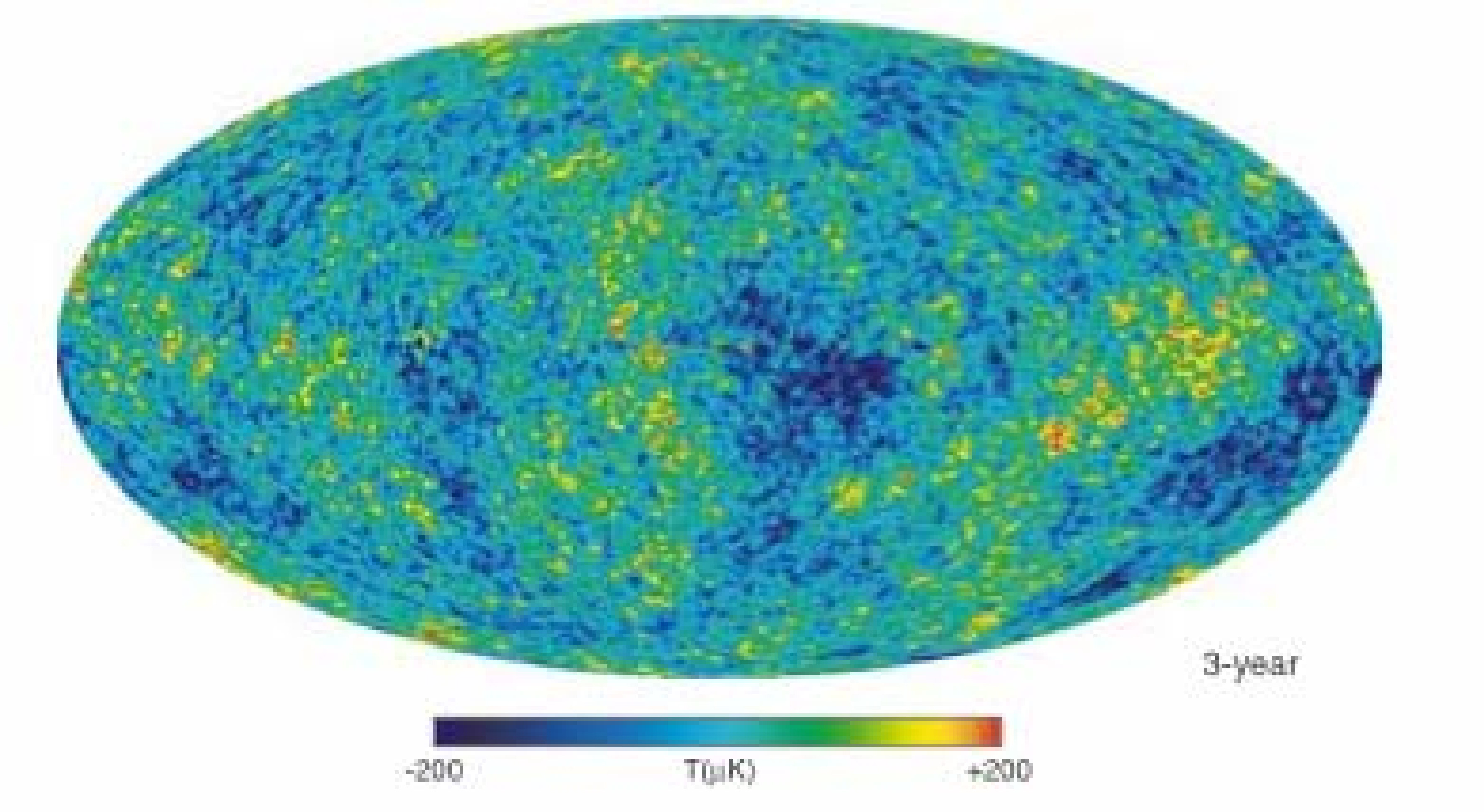
Beyond $C(\theta)$

- seeing the solar system in the microwave background

And back:

troubles in cosmological paradise

The WMAP Sky



NASA/WMAP Science team

Angular Power Spectrum

$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$

$C_\ell = (2\ell+1)^{-1} \sum_m |a_{\ell m}|^2$

$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\varphi)$

Standard model for the origin of fluctuations (inflation):

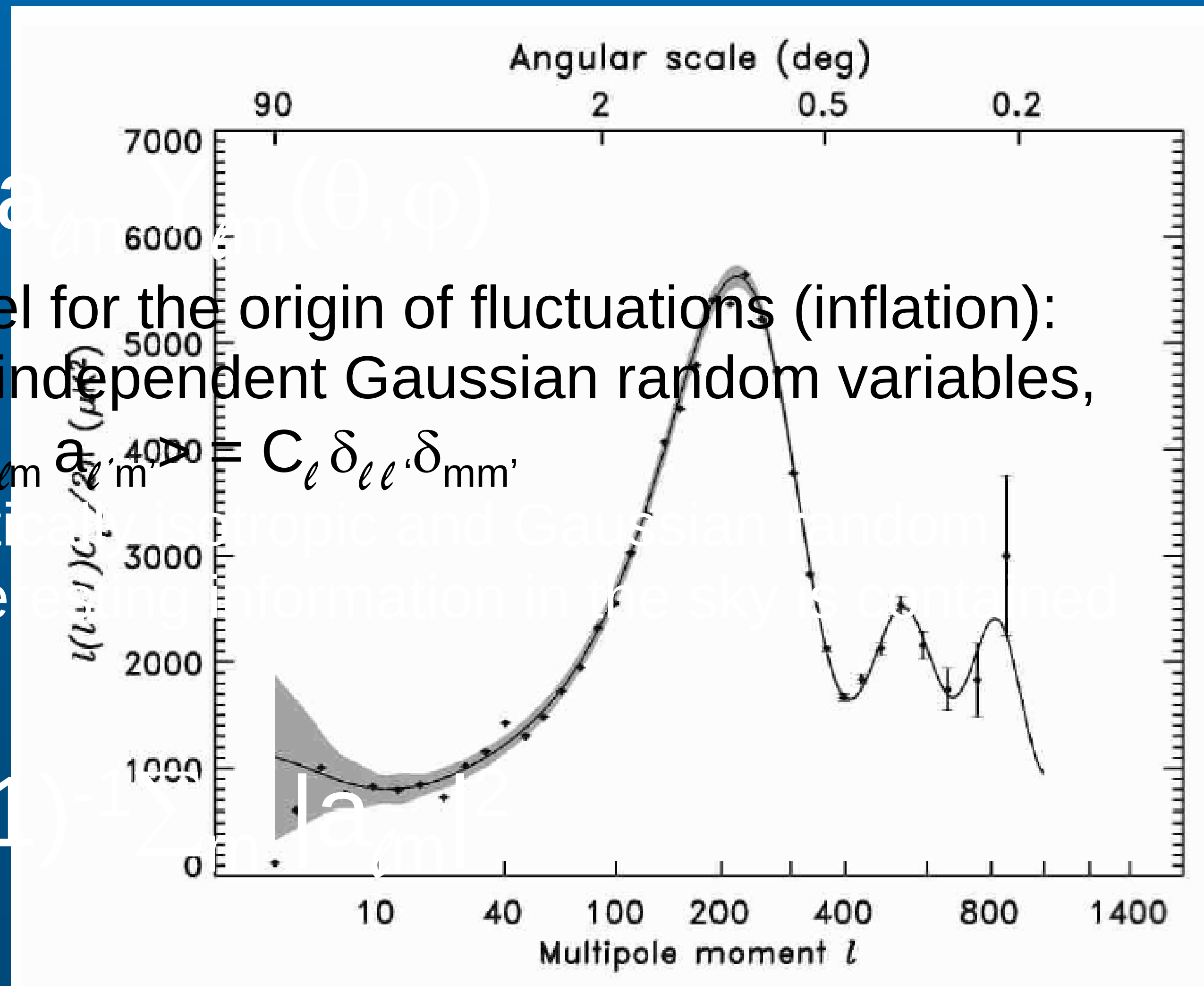
$a_{\ell m}$ are independent Gaussian random variables,

with $< a_{\ell m} a_{\ell' m'} > = C_\ell \delta_{\ell \ell'} \delta_{mm'}$

$\Rightarrow$Sky is statistically isotropic and Gaussian random:

ALL interesting information in the sky is contained in C_ℓ

$C_\ell = (2\ell+1)^{-1} \sum_m |a_{\ell m}|^2$



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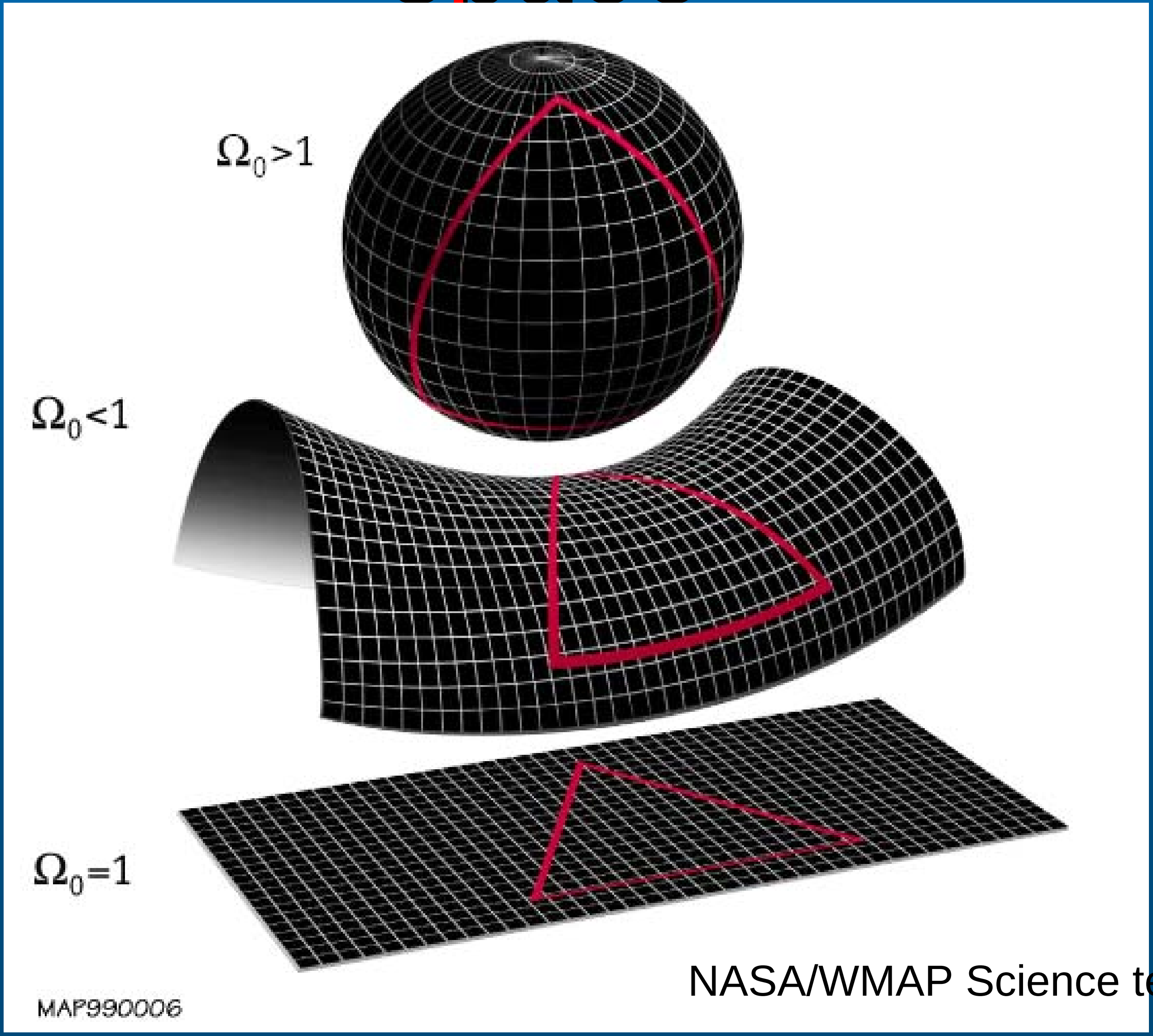
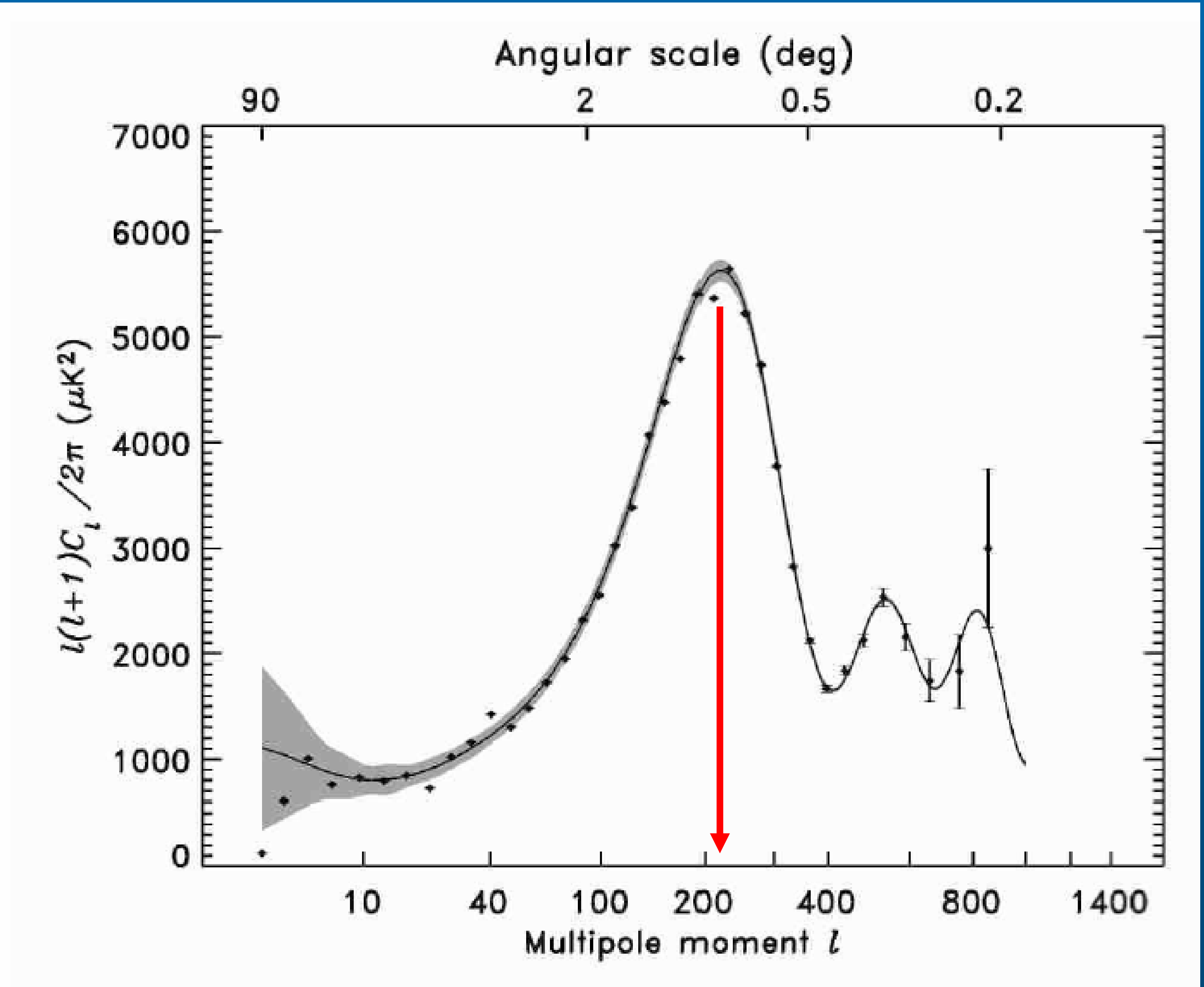
Measuring the shape of space



NASA/WMAP Science team

Angular Power Spectrum

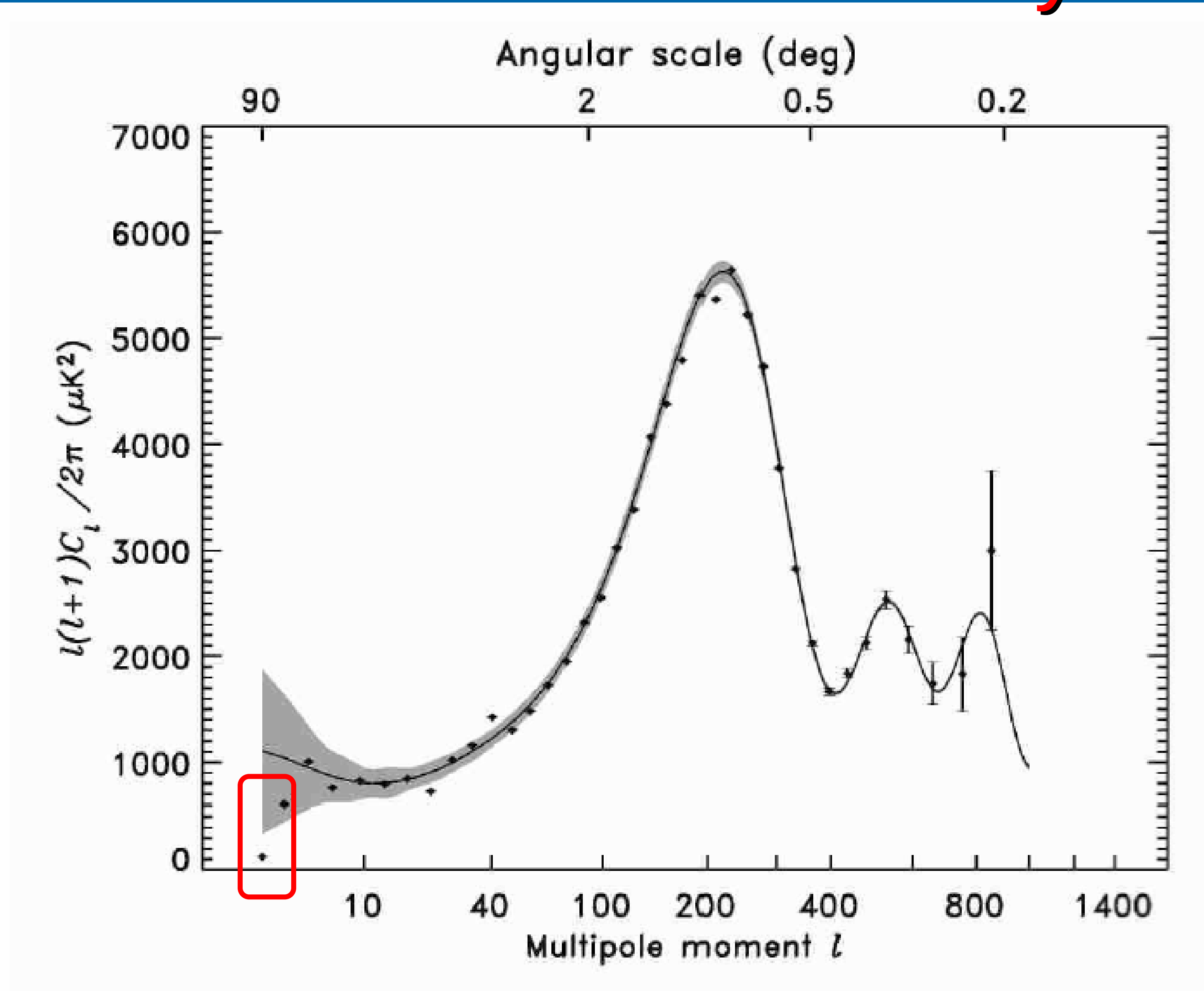


$\Omega = 1.02 \pm .02$

(with other data)

Is there anything interesting left to learn about the Universe on large scales?

Motivation: "The Low-l Anomaly"

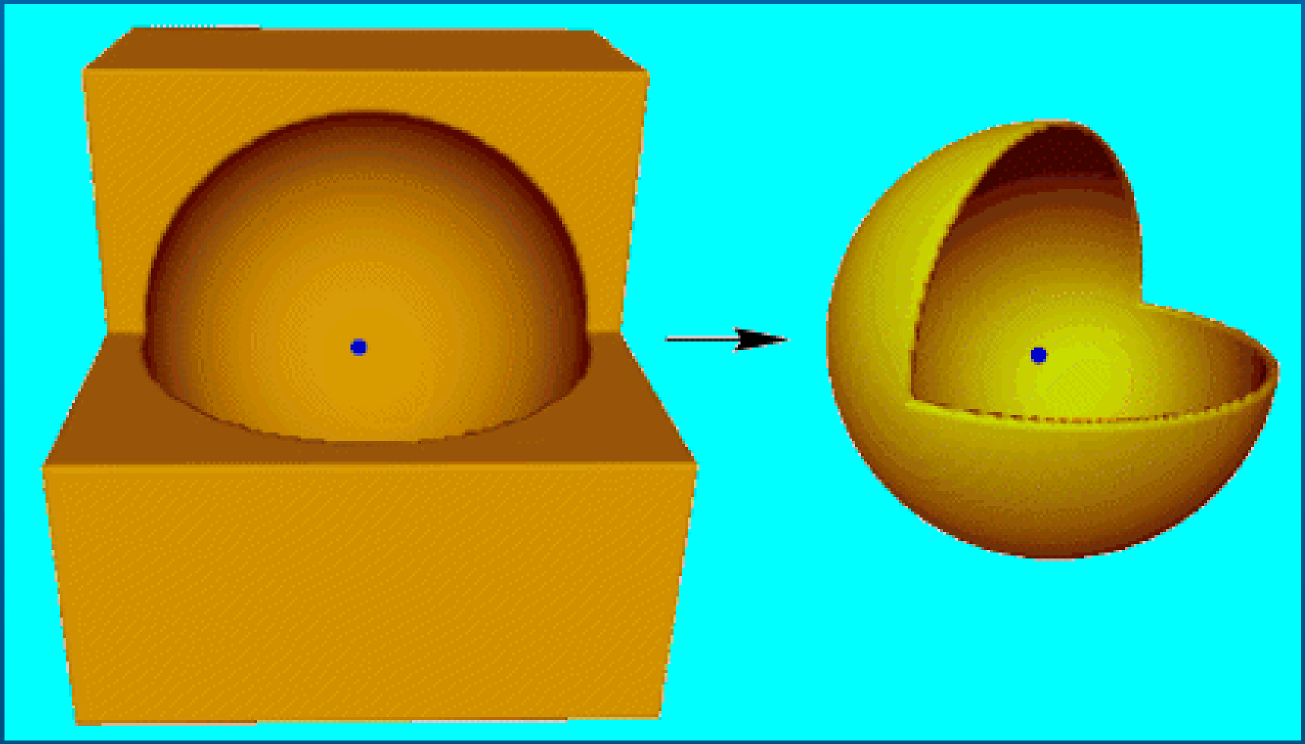


Explaining the Low-l Anomaly

1. "Didn't that go away?"
2. "I never believe *a posteori* statistics."
3. Cosmic variance -- "I never believe anything less than a (choose one:) 5σ 10σ 20σ result."
4. "Inflation can do that"
5. Other new physics

$\Rightarrow$ We must look beyond C_l 's and $C(\theta)$

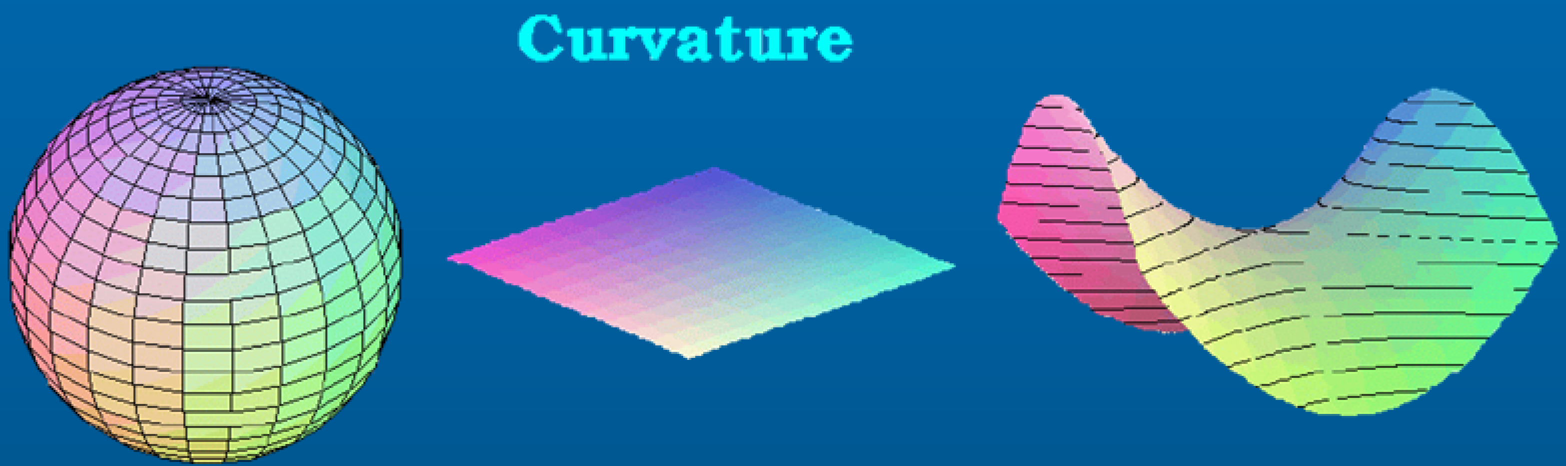
The microwave background in a “small” universe

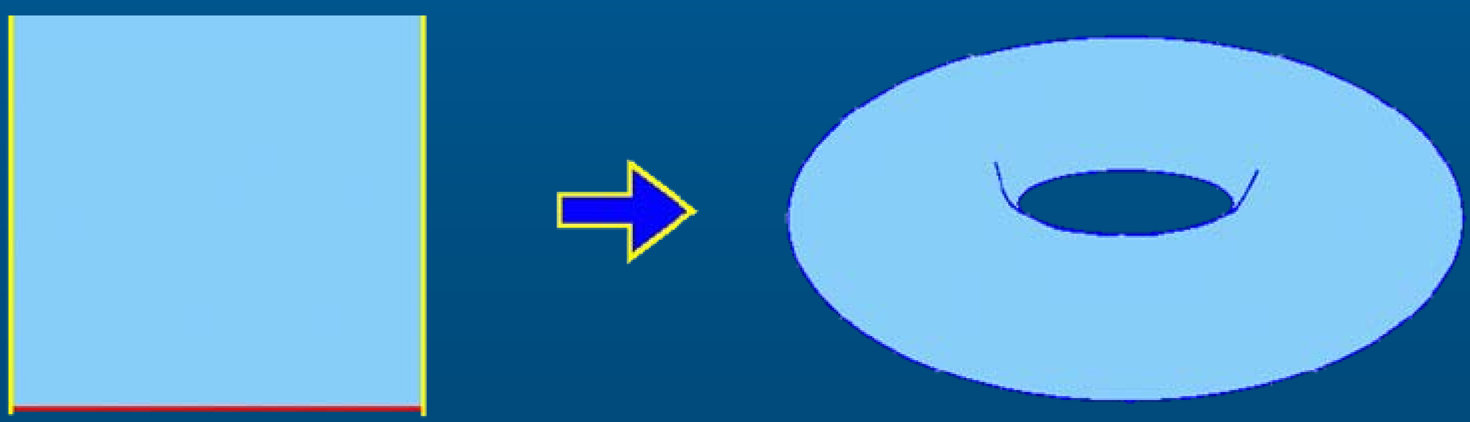


Absence of long wavelength modes ⇒

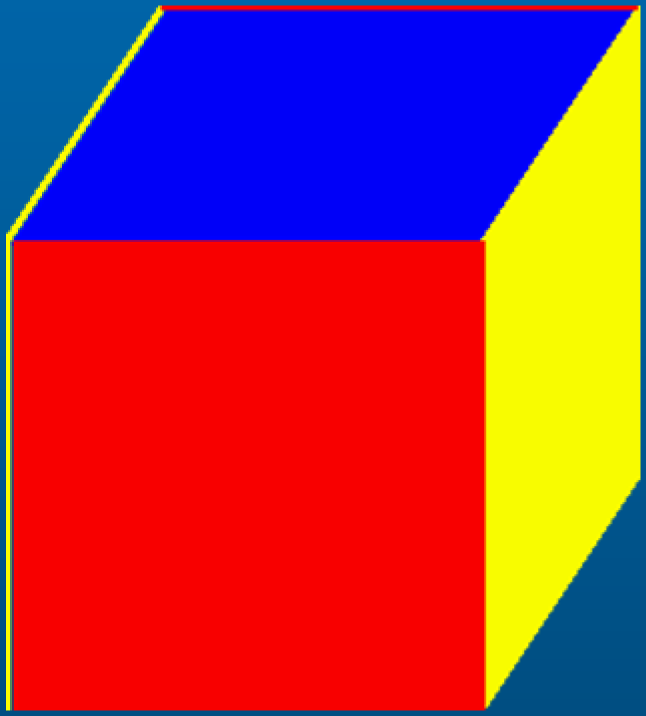
Absence of large angle correlations

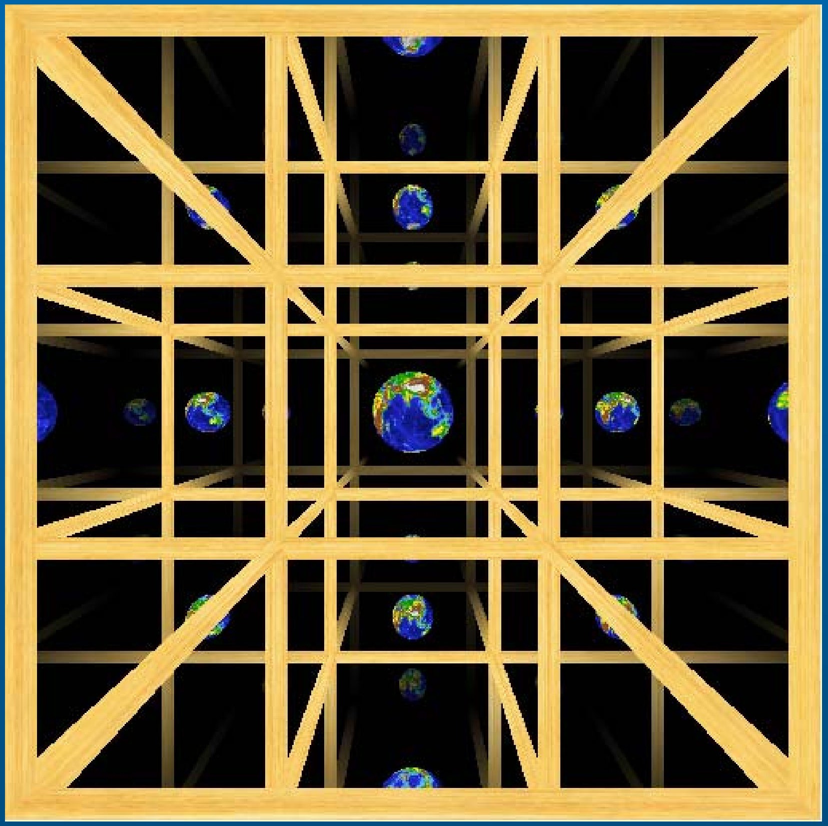
Measuring the shape of space





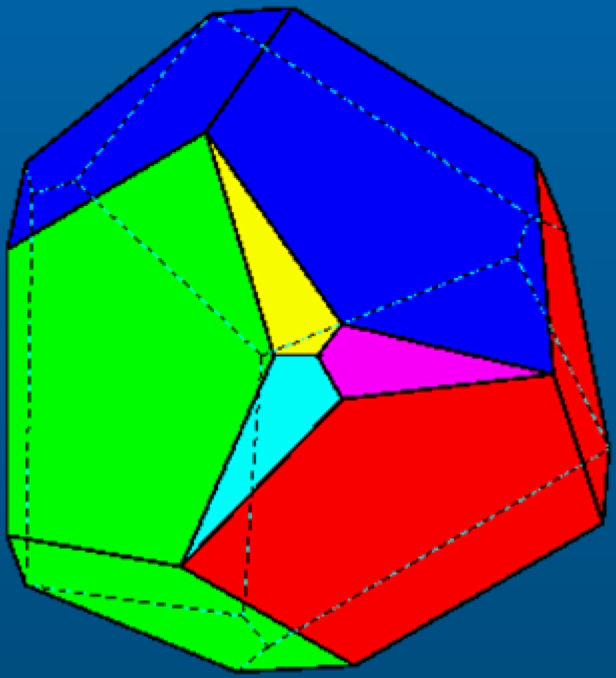
Three Torus

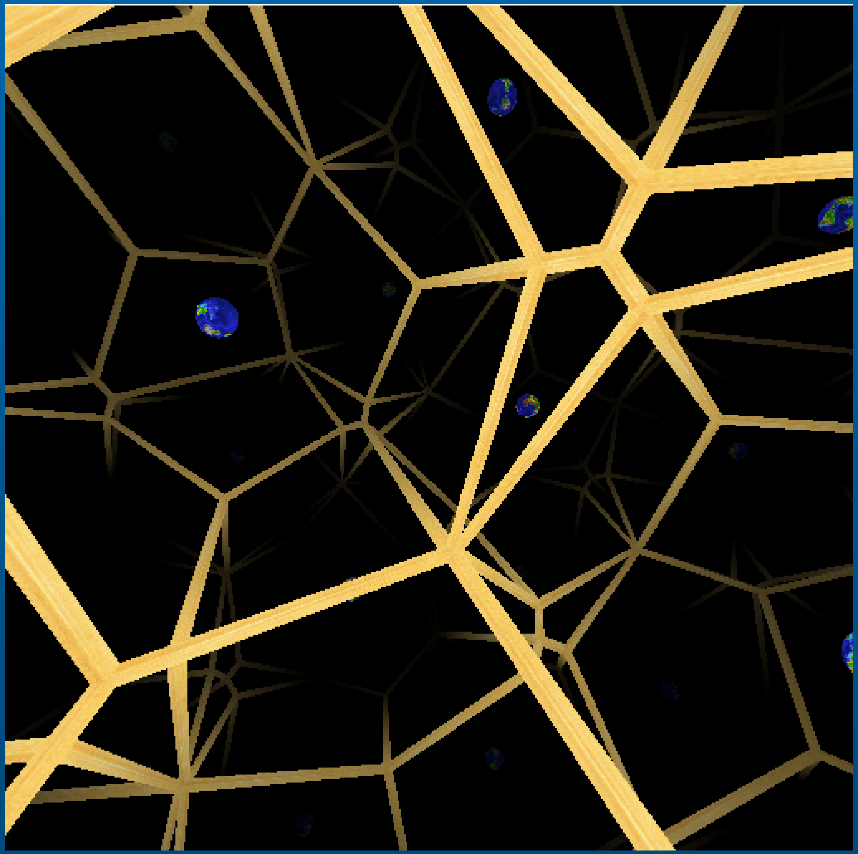




Same idea works in three space dimensions

Infinite number of tiling patterns

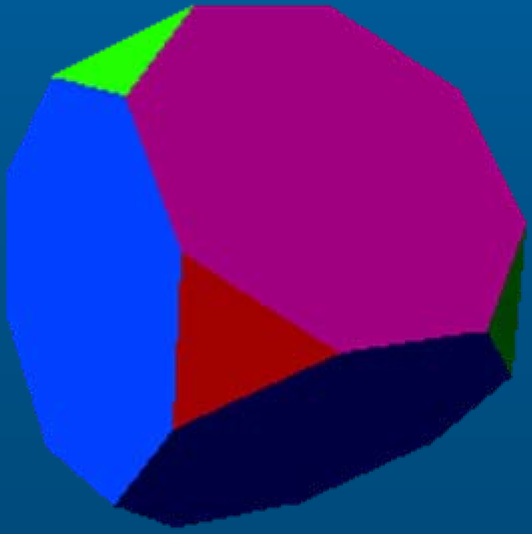


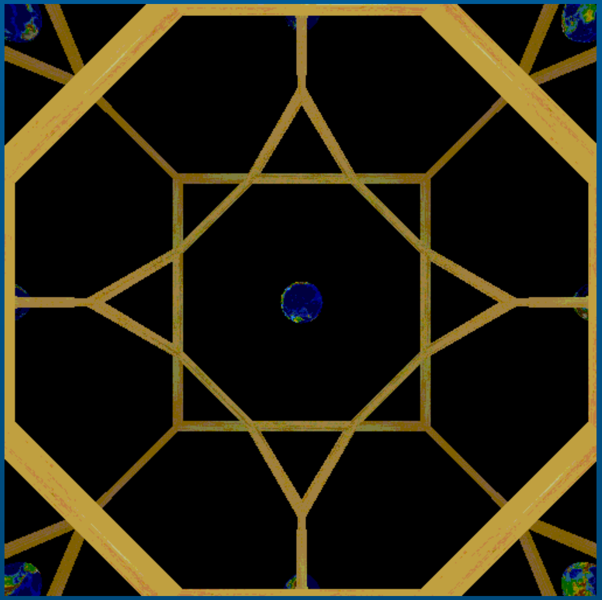


This one only works in hyperbolic space

Spherical Topologies

This example only works in spherical space





The microwave background in a multi-connected universe

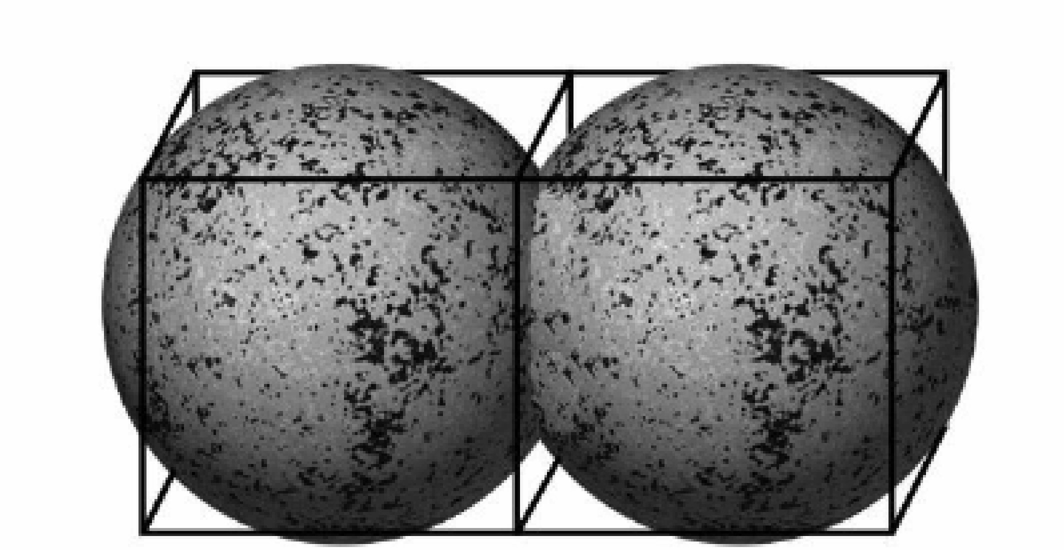
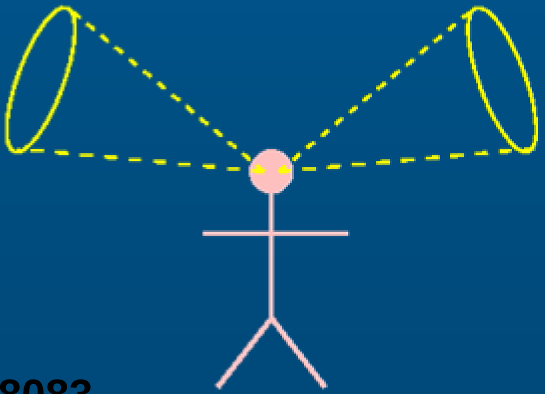
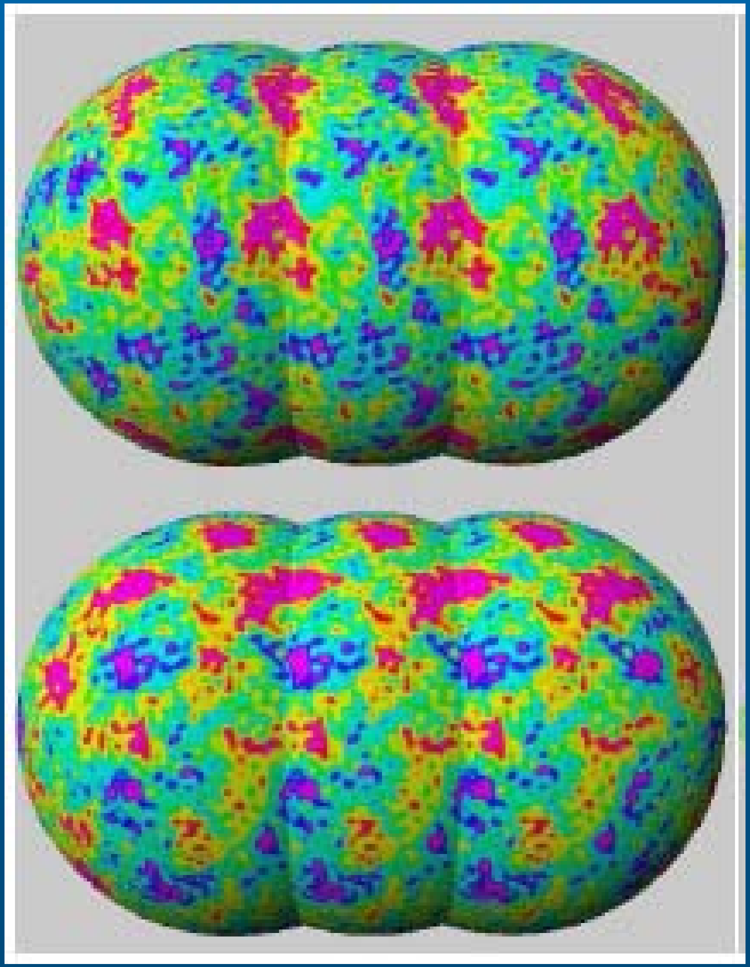


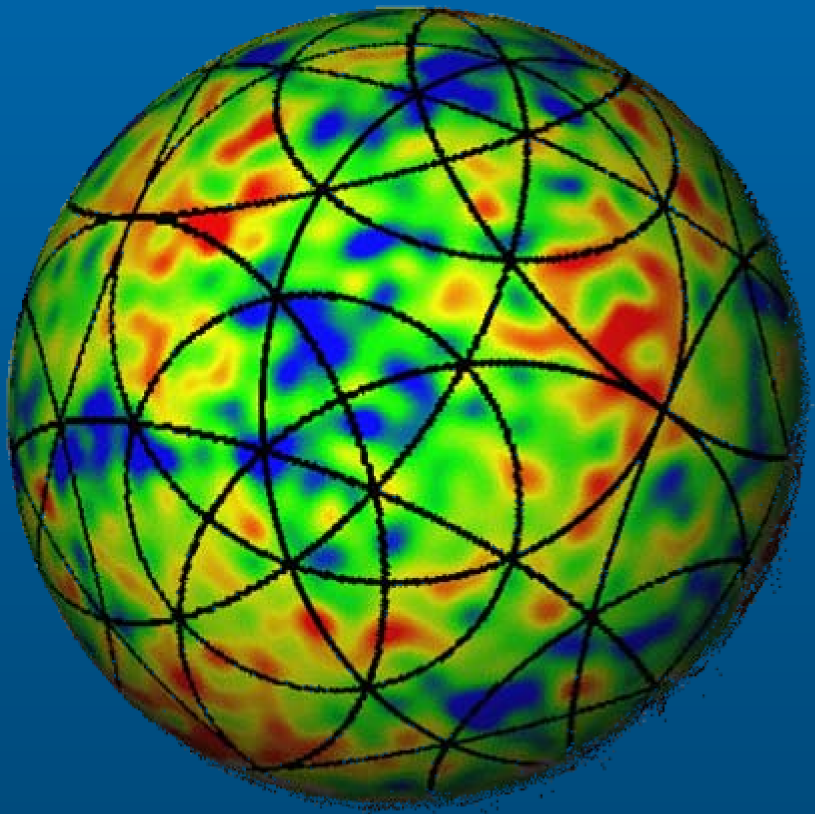
figure: J. Shapiro-Key



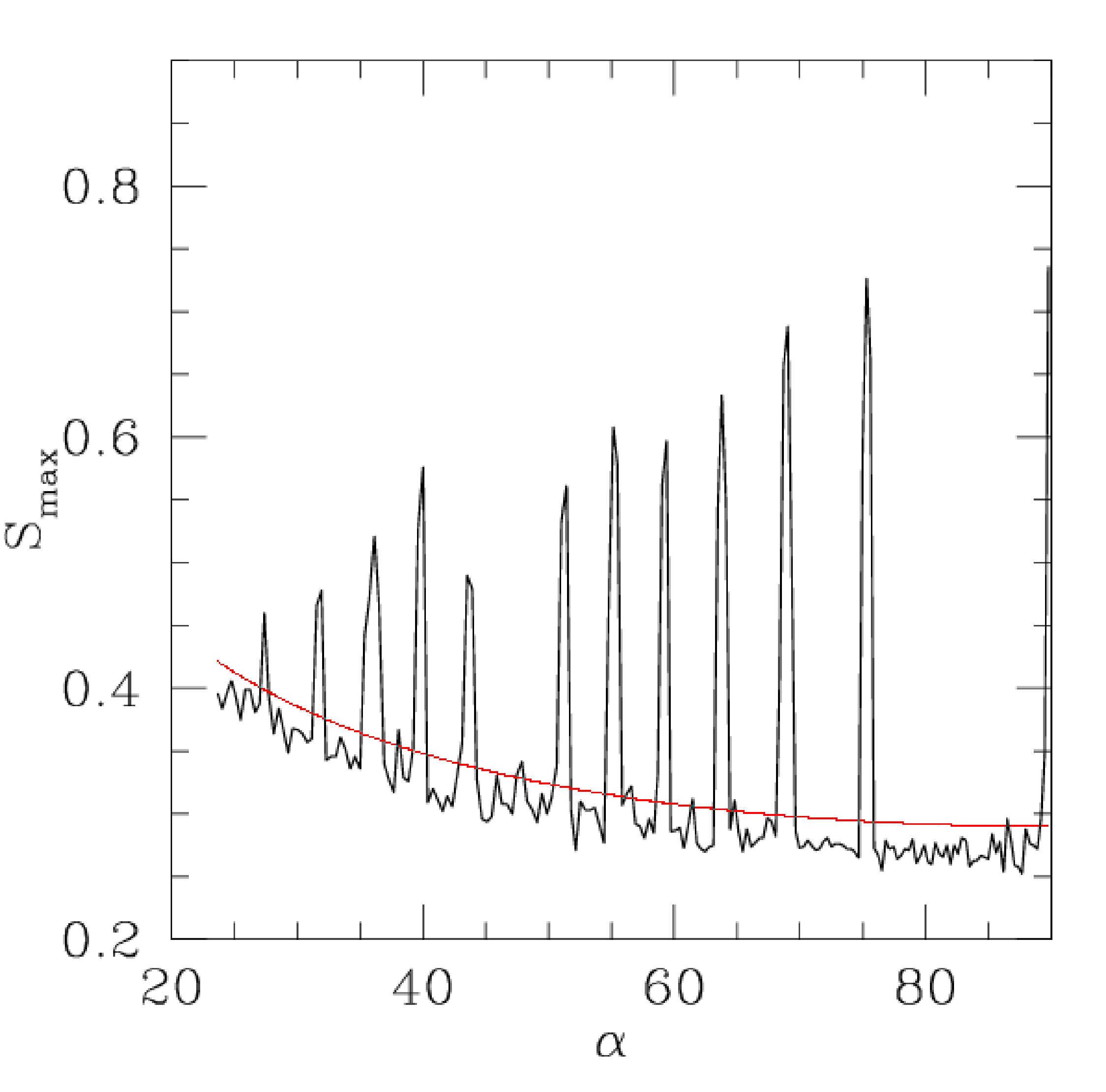
N. Cornish, D. Spergel, GDS **gr-qc/9602039**, **astro-ph/9708083, astro-ph/9708225, astro-ph/9801212**

Matched circles in a three torus universe



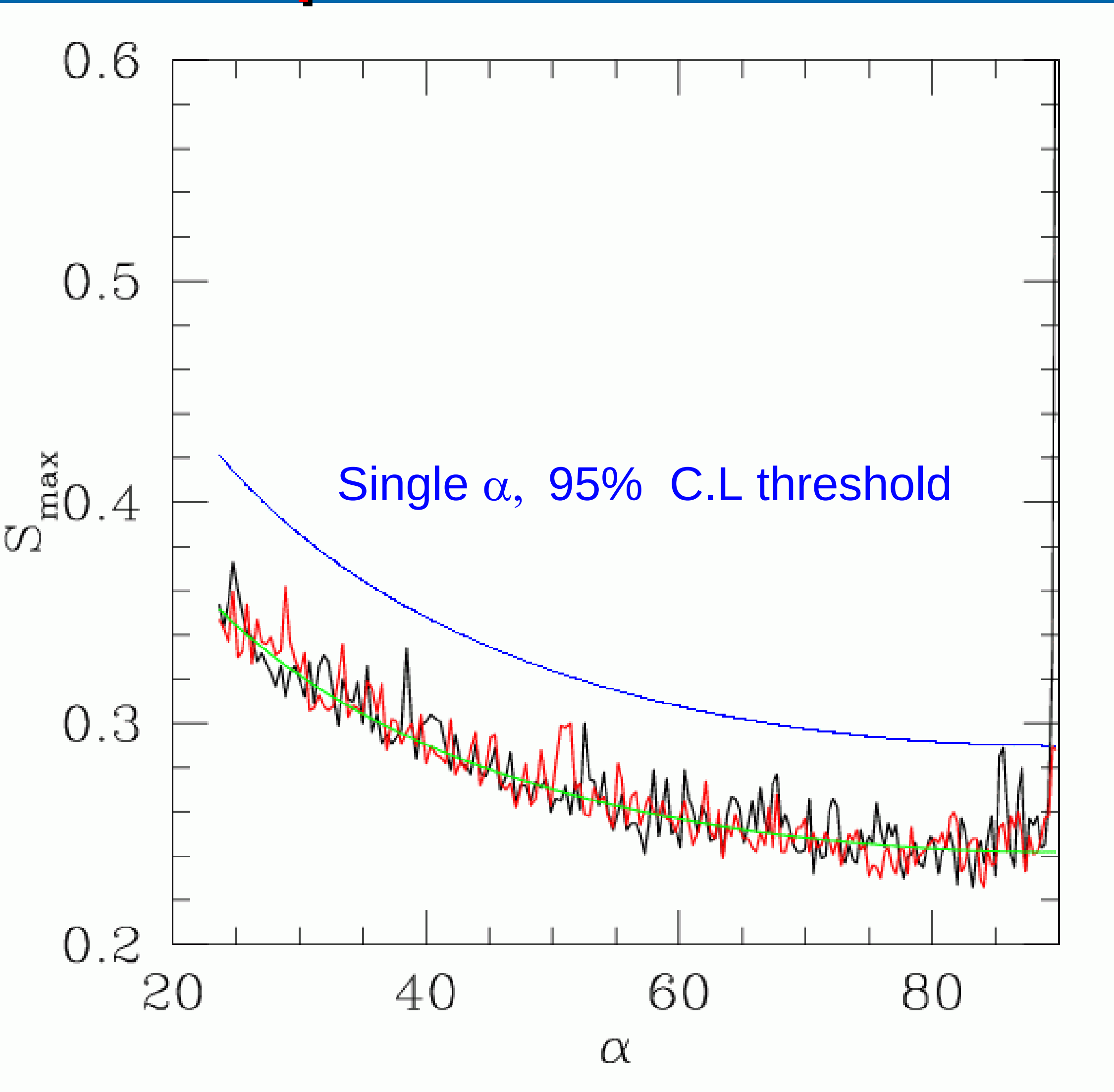


Matched Circles in Simulations



In a blind test >99% of circles found in a "deliberately difficult" universe

Searching the WMAP Sky: antipodal circles



Circle statistic on WMAP sky

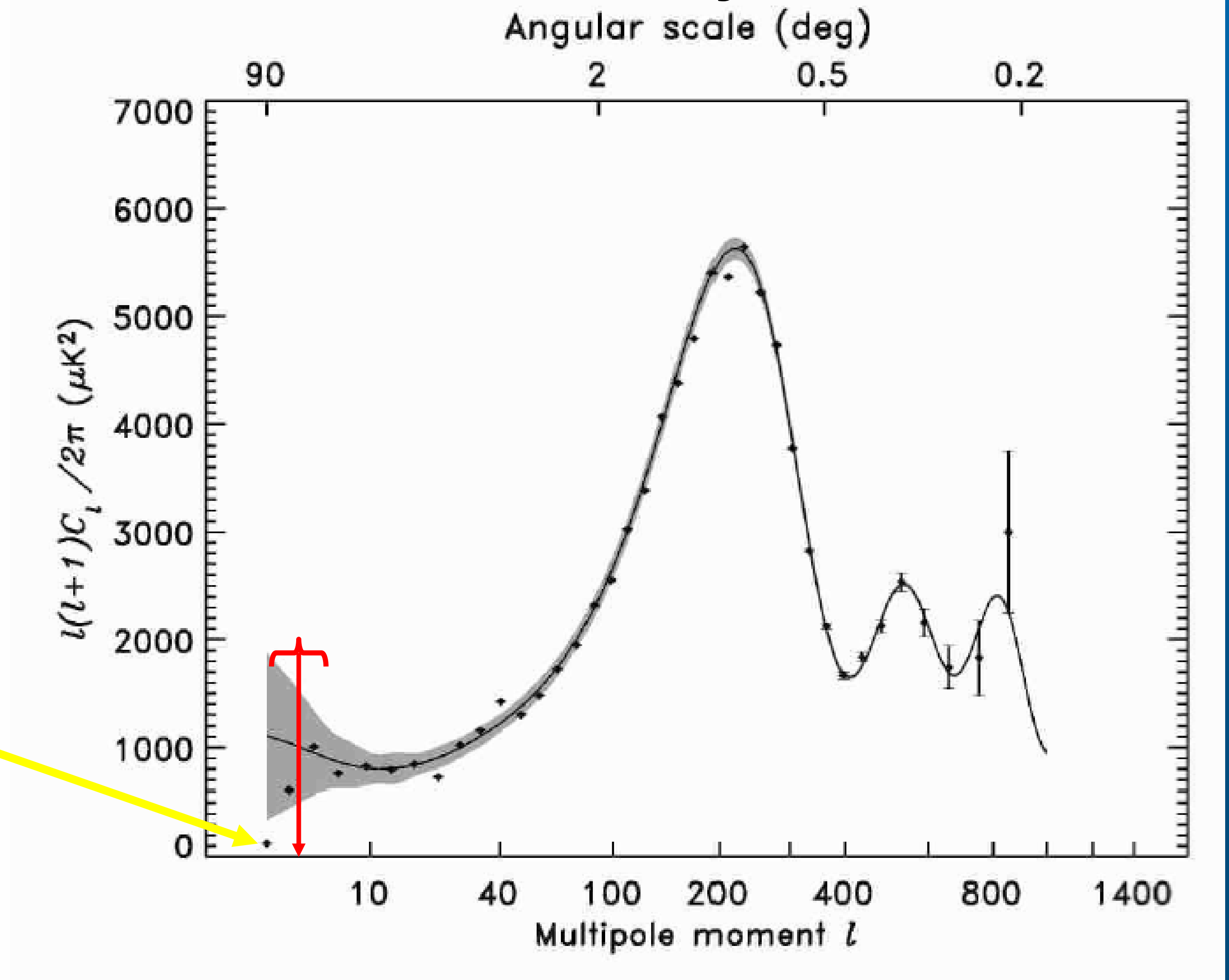
Implications

- No antipodal matched circles larger than 25^{o} at > 99% confidence
  - now extended to 20^{o} by pre-filtering.

- Unpublished: no matched circles > 25^{o}.
  - Universe is >90% of the LSS diameter (24 Gpc) across
  - Search is being repeated on 3-year data
  - Sensitivity should improve to 10^{o}-15^{o}

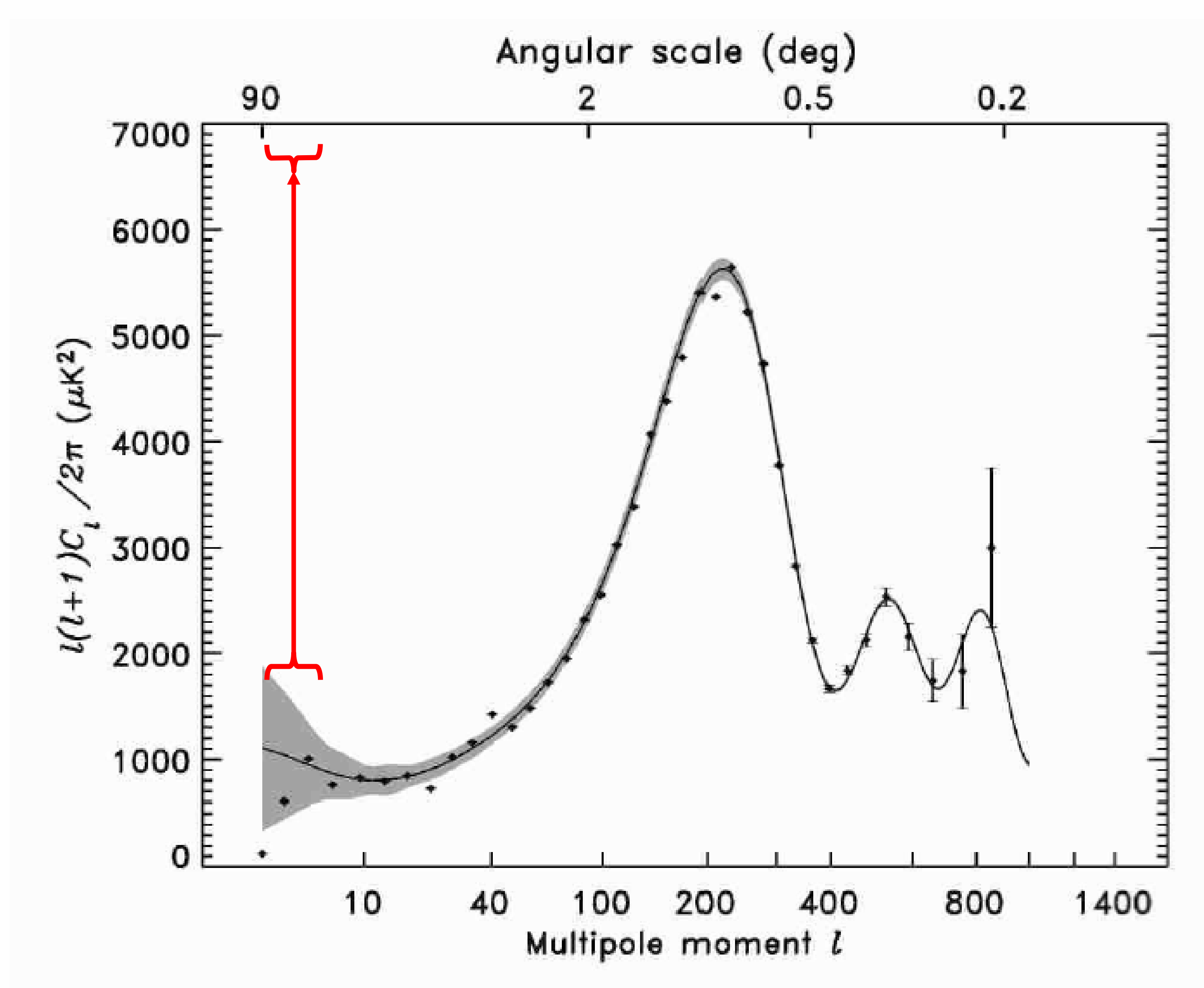
If there is topology, it's beyond (or nearly beyond) the horizon

"The Low-l Anomaly"



The low quadrupole

“The Large-Angle Anomaly”

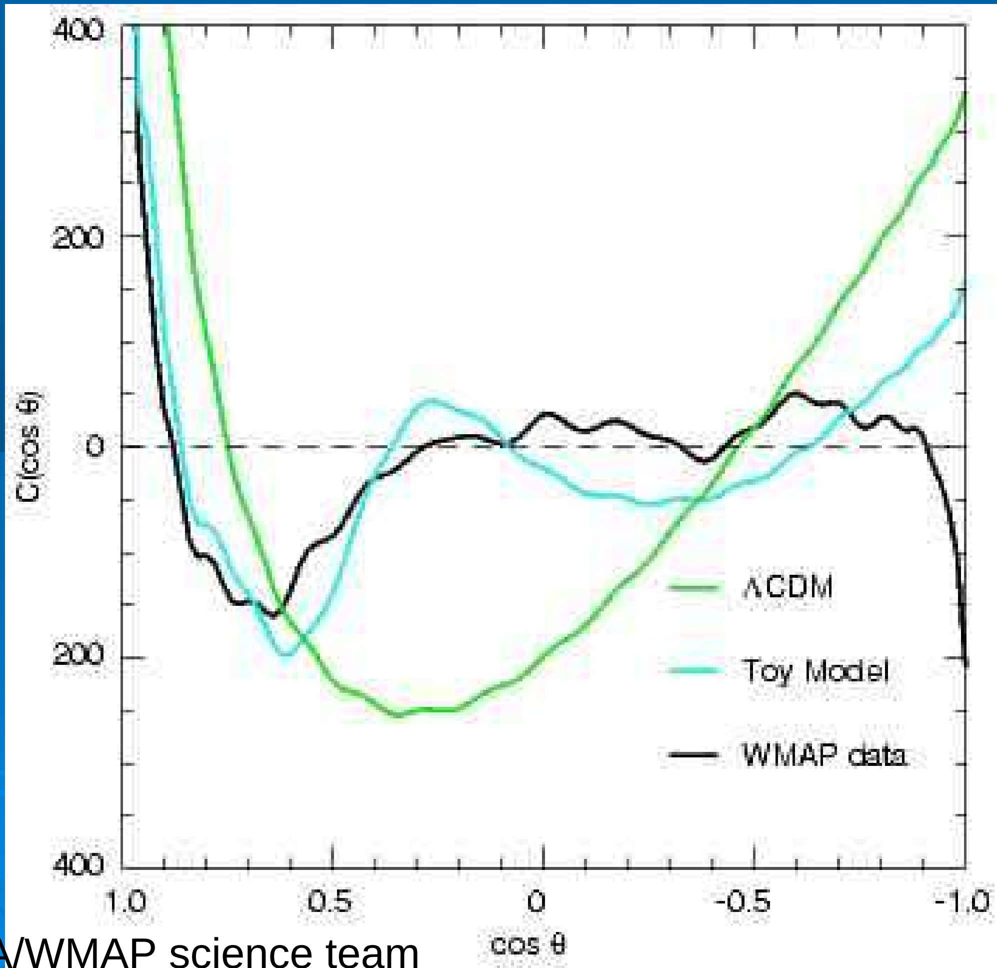


The Angular Correlation Function, C(θ)

$C(\theta) = \langle T(\Omega_1) T(\Omega_2) \rangle_{\Omega_1 . \Omega_2 = \cos\theta}$

But (established lore):
$C(\theta) = \sum_l C_l P_l(\cos(\theta))$

$\Rightarrow$ Same information as C_l, just differently organized



NASA/WMAP science team

IF

- $C(\theta)$ is obtained by a full sky average

or

- the sky is statistically isotropic, i.e. if $\langle a_{lm} a^*_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l$

Is the Large-Angle Anomaly Significant?

WMAP1:

$$S_{1/2} = \int_{-1}^{1/2} [C(\theta)]^2 \, d\cos\theta$$

Only 0.15% of realizations of **inflationary** ΛCDM universe with the best-fit parameters have lower S!

Beyond C_ℓ and $C(\theta)$:
Searches for Departures from Gaussianity/Statistical Isotropy

- angular momentum dispersion axes (da Oliveira-Costa, *et al.*)
- Genus curves (Park)
- Spherical Mexican-hat wavelets (Vielva *et al.*)
- Bispectrum (Souradeep *et al.*)
- North-South asymmetries in multipoint functions (Eriksen *et al.*, Hansen *et al.*)
- Cold hot spots, hot cold spots (Larson and Wandelt)
- Land & Magueijo scalars/vectors
- **multipole vectors**
  (Copi, Huterer & GDS; Schwarz, SCH; CHSS; also Weeks; Seljak and Slosar; Dennis)

Shape and Alignment of the Quadrupole and Octopole

A. de Oliveira-Costa, M. Tegmark, M. Zaldarriaga, A. Hamilton. **Phys.Rev.D69:063516,2004**
astro-ph/0307282

For each ℓ, find the axis $\mathbf{n}_\ell$ around which the angular momentum dispersion :

$$(\Delta L)^2 \equiv \Sigma_m m^2 |a_{\ell m}(\mathbf{n}_\ell)|^2$$

is maximized

Results:

	Probability
•octopole is unusually "planar" (dominated by $\|m\| = 3$ if $z \equiv \mathbf{n}_3$).	1/20??
• $\mathbf{n}_2 \cdot \mathbf{n}_3 = 0.9838$	1/60

Multipole Vectors

Q: What are the directions associated
with the ℓ th multipole:

$$\Delta T_\ell(\theta,\phi) \equiv \sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) \;\; ?$$

Dipole (ℓ =1) :

$$\sum_m \mathbf{a_{1m} Y_{1m}} (\theta,\phi) =$$

$$A^{(1)} \, (\hat{\mathbf{u}}_x^{(1,1)}, \hat{\mathbf{u}}_y^{(1,1)}, \hat{\mathbf{u}}_z^{(1,1)}) \, .(\sin\theta \cos\phi, \sin\theta \sin\phi, \cos\theta)$$

Advantages: 1) $\hat{\mathbf{u}}^{(1,1)}$ is a vector, $A^{(1)}$ is a scalar

2) Only $A^{(1)}$ depends on C_1

Multipole Vectors

General ℓ, write:

$$\sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) \approx A^{(\ell)} [(\hat{u}^{(\ell,1)} \cdot \hat{e}) \ldots (\hat{u}^{(\ell,\ell)} \cdot \hat{e}) \text{ - all traces}]$$

$\{\{a_{\ell m},\ m=-\ell,\ldots,\ell\},\ \ell = (0,1,)2,\ldots\} \Rightarrow$

$\{A^{(\ell)}, \{\hat{u}^{(\ell,i)}, \ell = 1,\ldots \ell\}, \ell = (0,1,)2,\ldots\}$

Advantages: 1) $\hat{\mathbf{u}}^{(\ell,i)}$ are vectors, $A^{(\ell)}$ is a scalar

2) Only $A^{(\ell)}$ depends on C_ℓ

Maxwell Multipole Vectors

$$\sum_m a_{\ell m} Y_{\ell m}(\theta,\phi) = \left[(\mathbf{u}^{(\ell,1)} \cdot \nabla) \ldots (\mathbf{u}^{(\ell,\ell)} \cdot \nabla) r^{-1} \right]_{r=1}$$

manifestly symmetric AND trace free:

$$\nabla^2 (1/r) \propto \delta(r)$$

J.C. Maxwell, *A Treatise on Electricity and Magnetism*, v.1, 1873 (1st ed.)

Area Vectors

Notice:

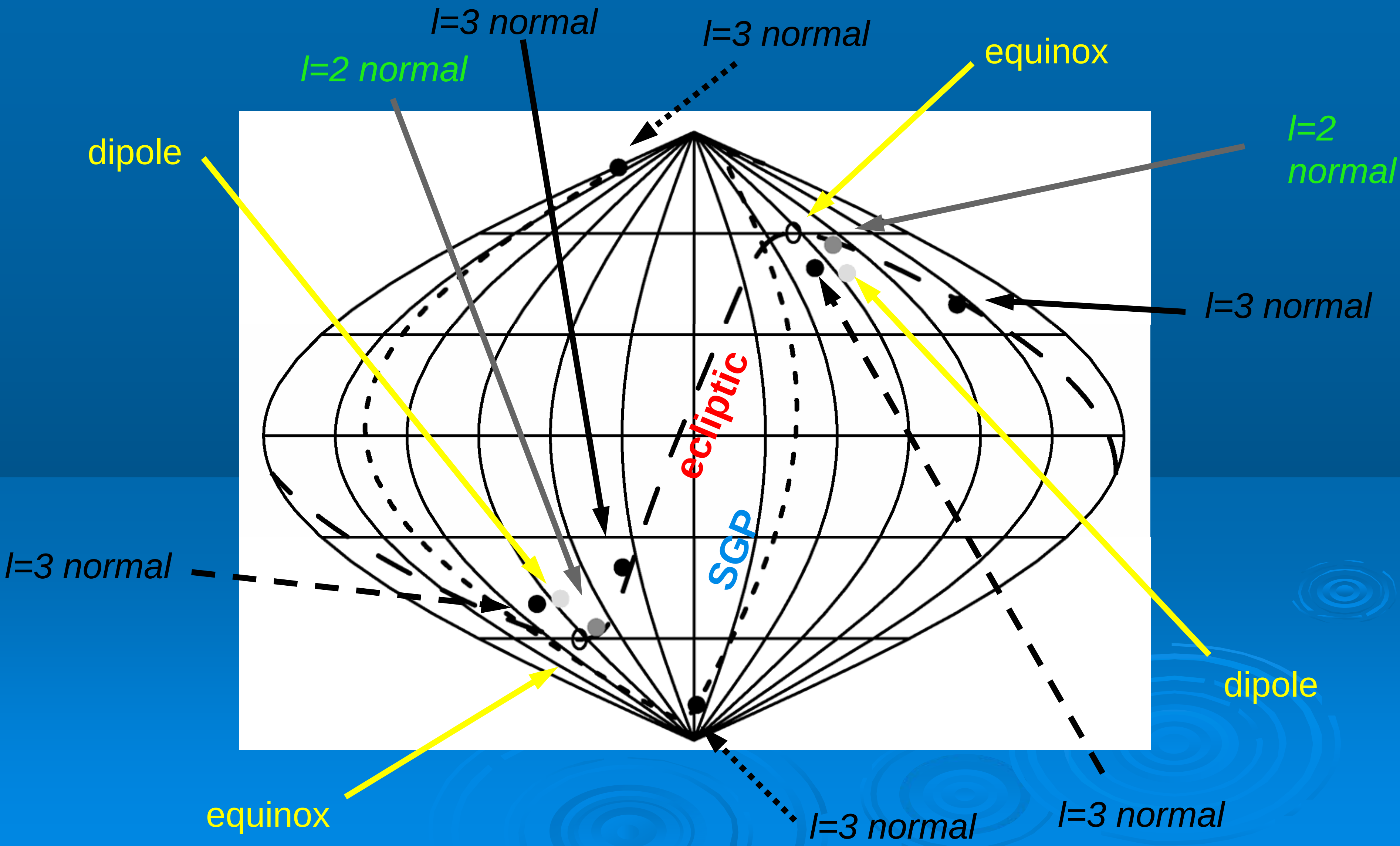
- Quadrupole has 2 vectors, *i.e.* quadrupole is a plane
  - $n_2 \parallel (\hat{u}^{(2,1)} \times \hat{u}^{(2,2)})$
- Octopole has 3 vectors, *i.e.* octopole is 3 planes
  - octopole is perfectly planar if
    $(\hat{u}^{(3,1)} \times \hat{u}^{(3,2)}) \parallel (\hat{u}^{(3,2)} \times \hat{u}^{(3,3)}) \parallel (\hat{u}^{(3,3)} \times \hat{u}^{(3,1)})$
    and then: $n_3 \parallel (\hat{u}^{(3,1)} \times \hat{u}^{(3,2)})$

Suggests defining:

$\mathbf{w}^{(\ell,i,j)} \equiv (\hat{u}^{(\ell,i)} \times \hat{u}^{(\ell,j)})$ “area vectors”

Carry some, but not all, of the information

l=2&3 Multiple Vectors

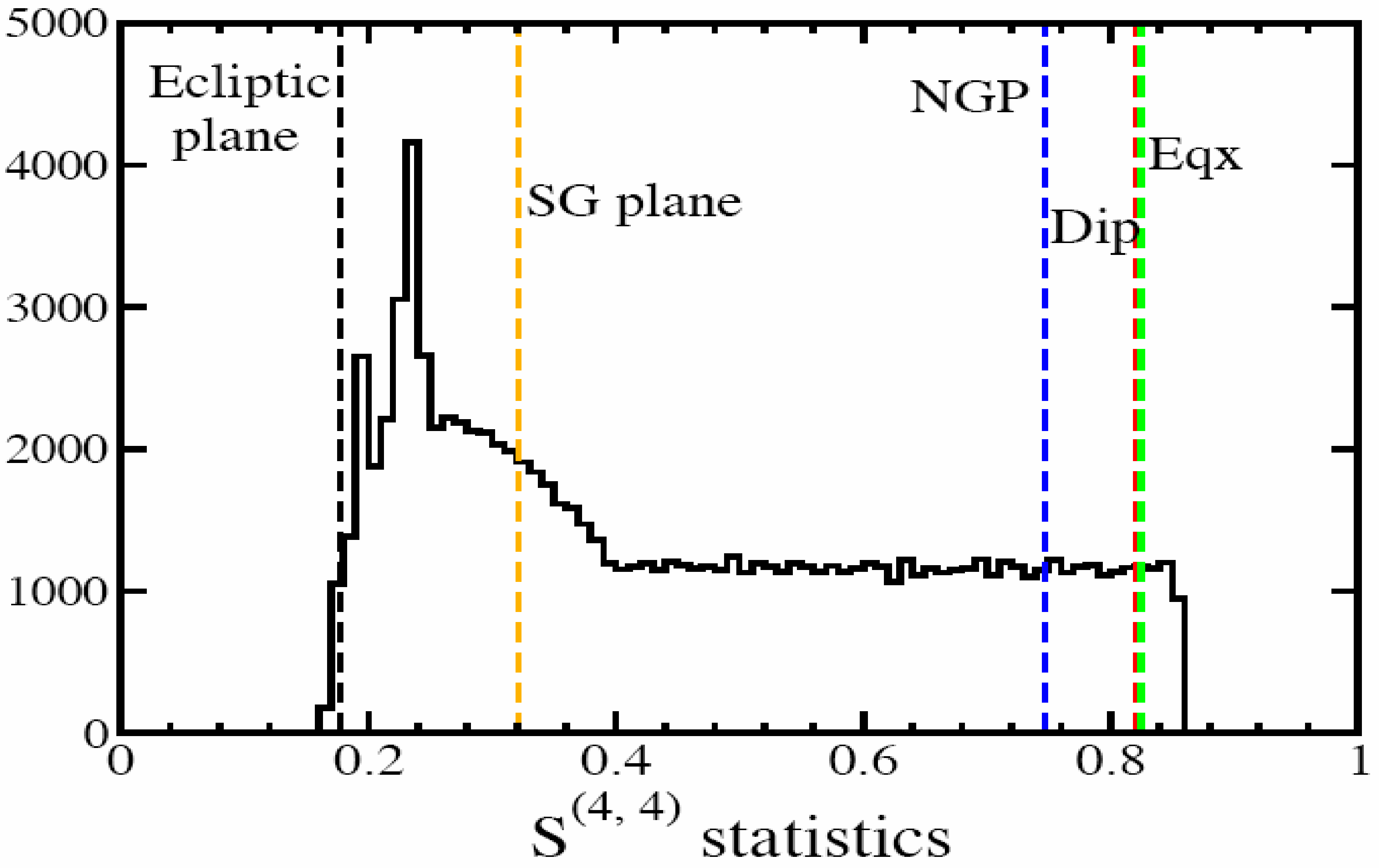


Alignment probabilities

Test	TOH DQ-corr	LILC DQ-corr	ILC DQ-corr	TOH uncorr	LILC uncorr	ILC uncorr
A_i	0.117	0.602	0.289	0.582	2.622	0.713
D_i	1.246	1.309	2.240	1.262	1.309	2.567
ecliptic plane	1.425	1.480	2.006	1.228	1.735	2.724
NGP	0.734	0.940	0.508	0.909	1.265	0.497
SG plane	14.4	13.4	8.9	11.6	10.2	6.5
dipole	0.045	0.214	0.110	0.093	0.431	0.207
equinox	0.031	0.167	0.055	0.064	0.315	0.080

All values in %, in a sample of 100,000 MC realisations of Gaussian-random $a_{\ell m}$

Additional alignment of the observed quadrupole+octopole with physical directions

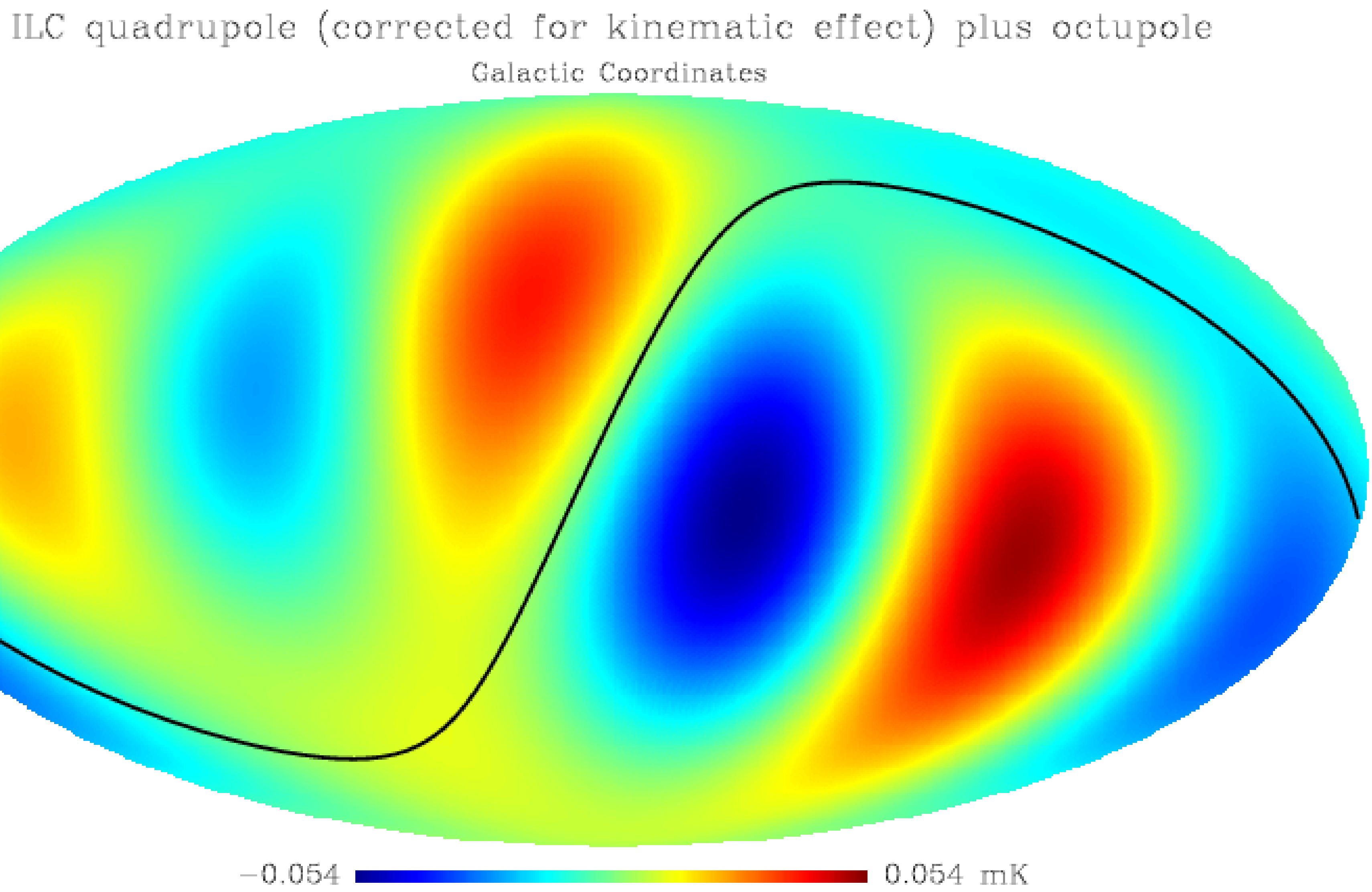


Area vectors tell about the orientations of the normals of the multipole planes

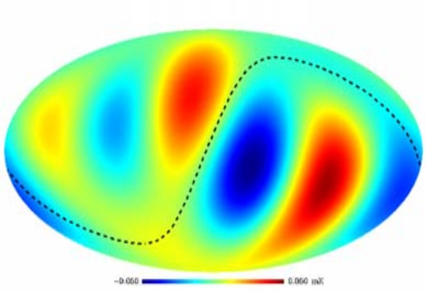
DON'T include all the information (multipole vectors do)

Can rotate the aligned planes about their common axis!

l=2&3 : The Map

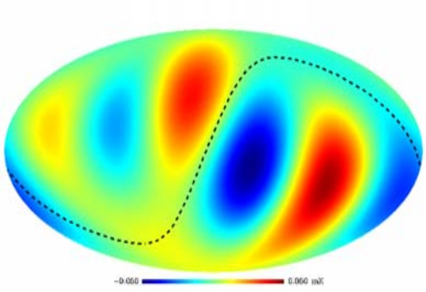

ILC quadrupole (corrected for kinematic effect) plus octupole
Galactic Coordinates
−0.054
0.054 mK

Quadrupole+Octopole Correlations -- Explanations: Cosmology?



- Cosmology -- you’ve got to be kidding? you choose: the dipole or the ecliptic ?

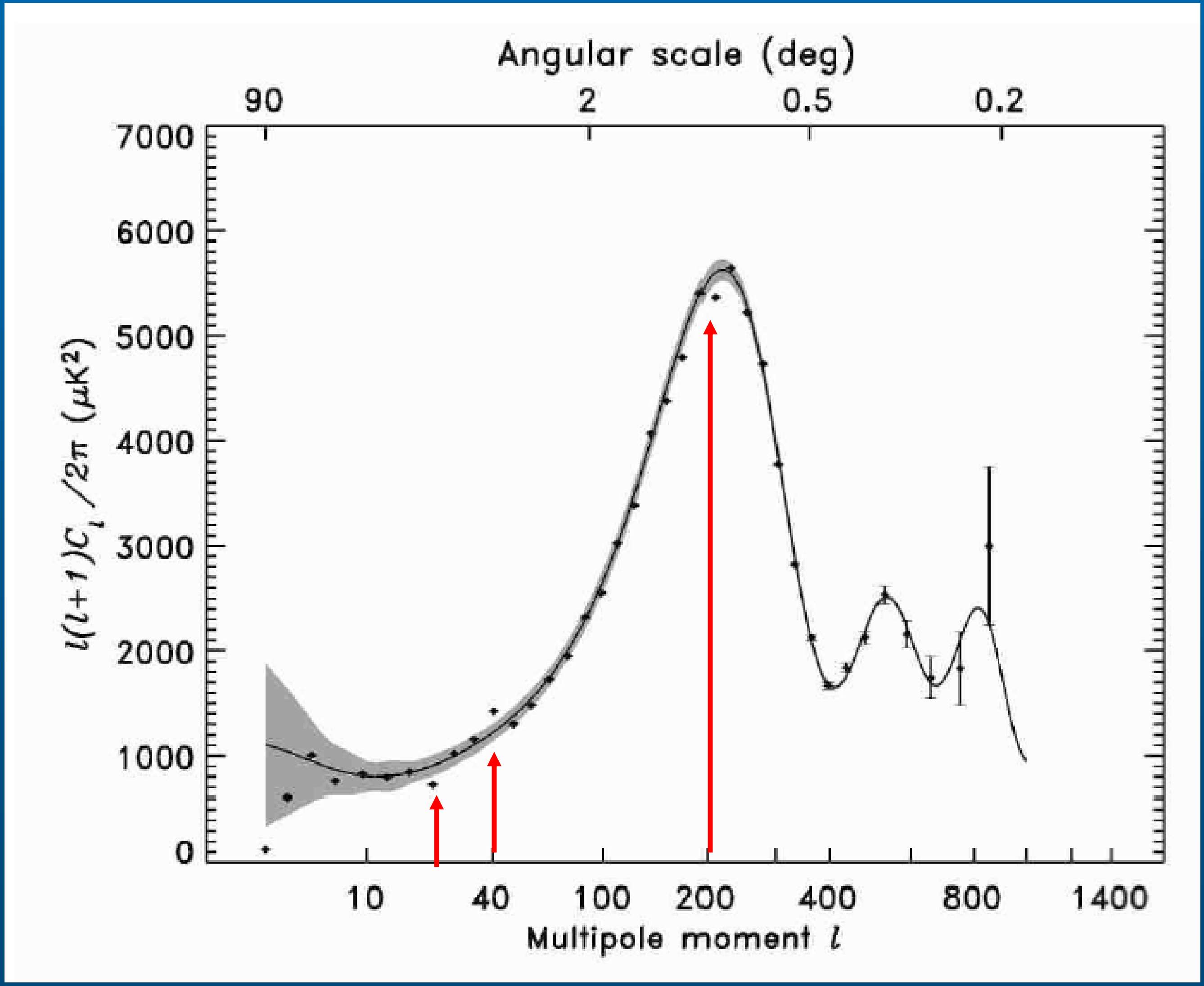
Quadrupole+Octopole Correlations -- Explanations: Systematics?



- Cosmology

- Systematics -- but …
  how do you get such an effect?
  esp., how do you get a N-S ecliptic asymmetry? (dipole mis-subtraction?)
  how do you avoid oscillations in the time-ordered data?
  possibilities -- correlation of beam asymmetry with observing pattern (S. Myer)

Angular Power Spectrum



At least 3 other major deviations in the C_l in 1st year data

Power spectrum: ecliptic plane vs. poles

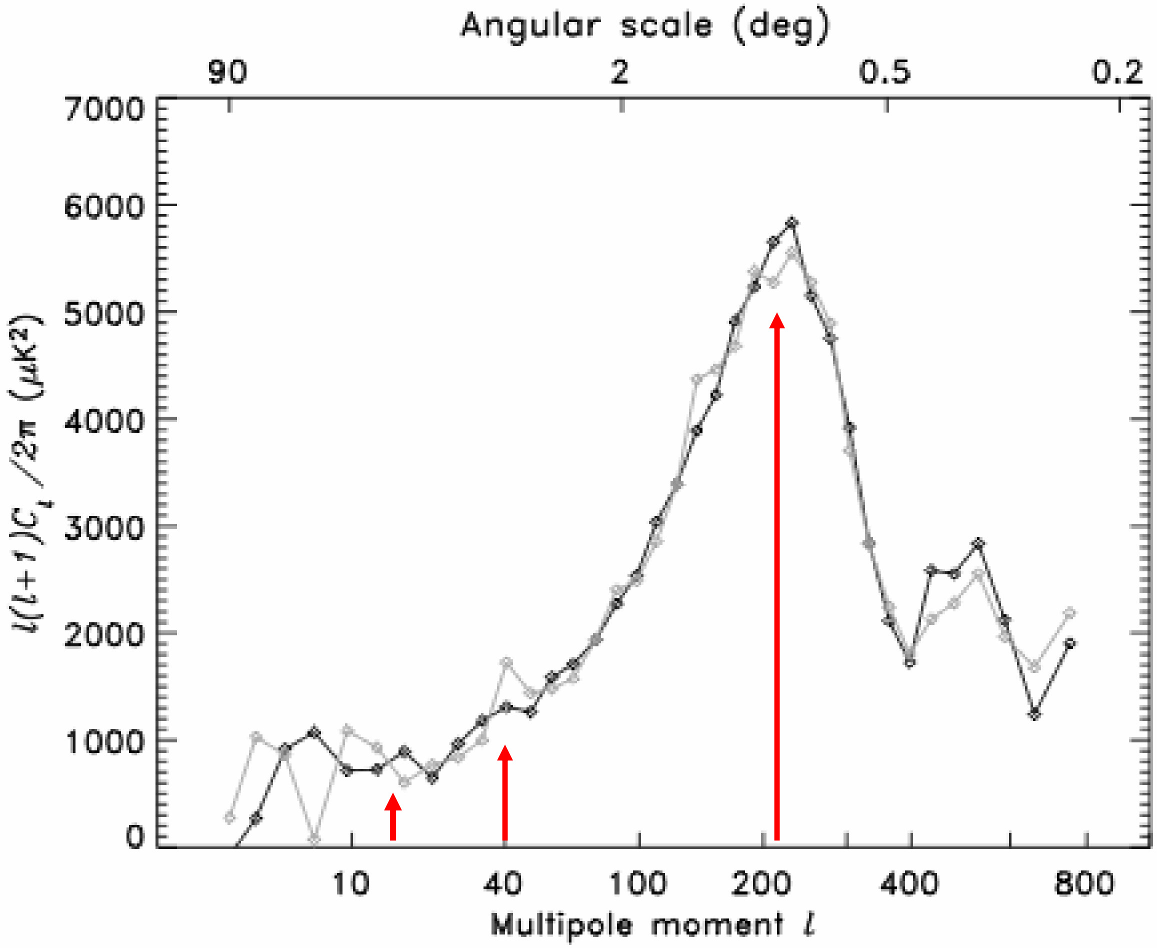
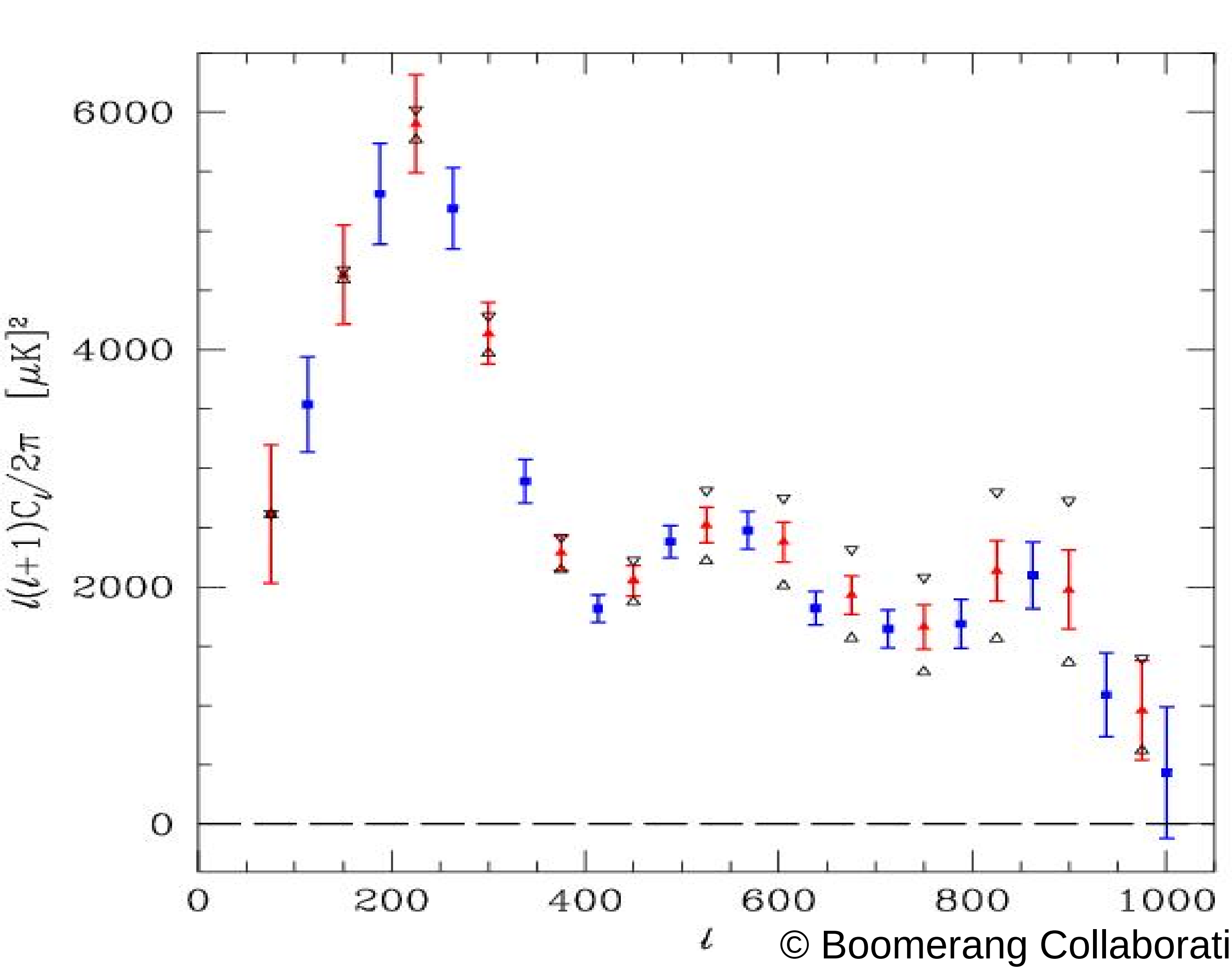


Fig. 7.— A comparison of the power spectrum computed with data from the ecliptic plane (black) vs. data from the ecliptic poles (grey). Note that some of the "bite" features that appear in the combined spectrum are not robust to data excision. There is also no evidence that beam ellipticity, which would be more manifest in the plane than in the poles, systematically biases the spectrum. This is consistent with estimates of the effect given by Page et al. (2003a).

"First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: The Angular Power Spectrum"
G. Hinshaw, et.al., 2003, ApJS, **148**, 135 --
only v.1 on archive

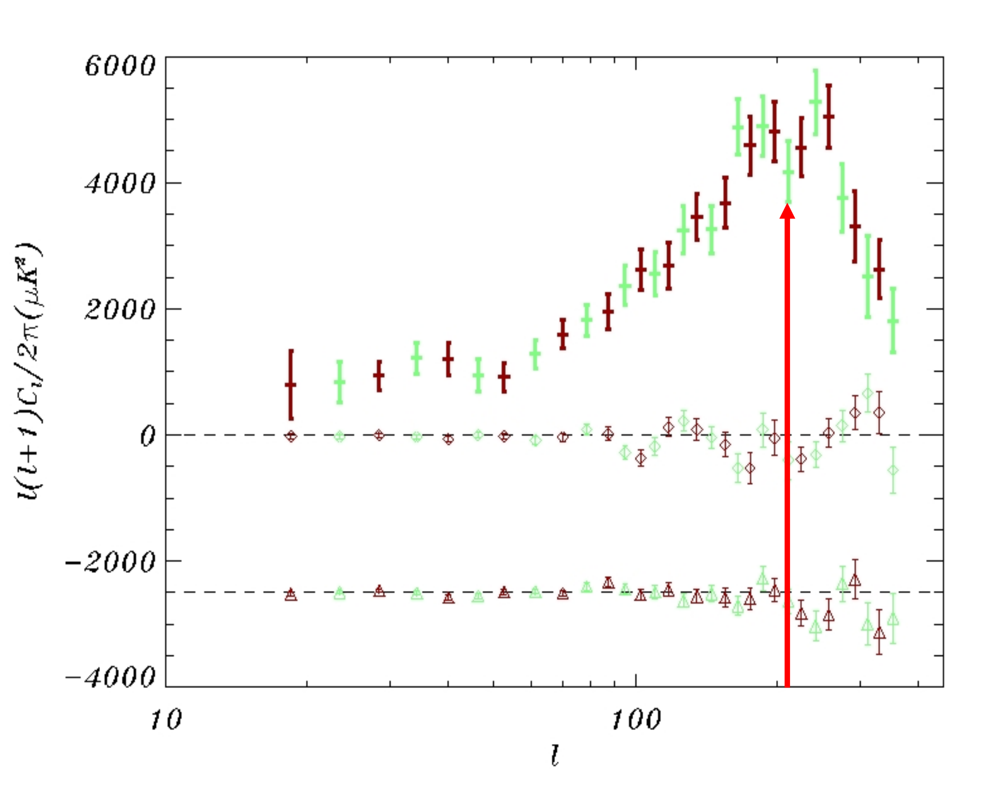
All 3 other major deviations are in the ecliptic polar C_ℓ only!!

No Dip?

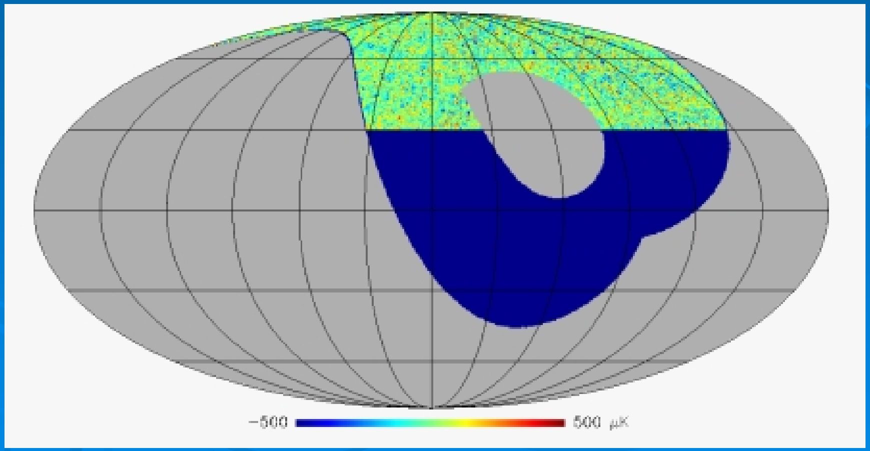


6000
4000
2000
0
$\ell(\ell+1)C_\ell/2\pi$ [μK]^2
0
200
400
600
800
1000
ℓ

The case against a systematic (cont.)

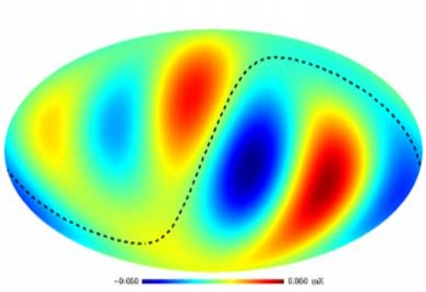


Archeops



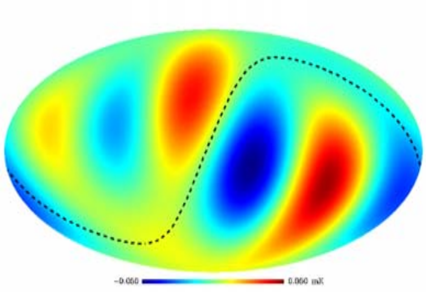
Archeops

Quadrupole+Octopole Correlations -- Explanations: more galaxy?



- Cosmology
- Systematics
- The Galaxy:
  - has the wrong multipole structure (shape)
  - is likely to lead to GALACTIC not ECLIPTIC/DIPOLE/EQUINOX correlations

Quadrupole+Octopole Correlations -- Explanations: Foregrounds?



- Systematics
- Cosmology
- The Galaxy
- Foregrounds -- difficulties:
    1. Changing a patch of the sky typically gives you: Y_{l0}
    2. Sky has 5x more octopole than quadrupole
    3. How do you get a physical ring <u>perpendicular</u> to the ecliptic
       Caution: can add essentially arbitrary dipole, which can entirely distort the ring! (Silk & Inoue)
    4. How do you hide the foreground from detection? $T \approx T_{CMB}$

Did WMAP123 change the (large angle) story?

Mildly changed quadrupole:

- time dependence of satellite temperature
- "galaxy bias correction" -- add power inside "galaxy cut"

Reported something different for C_l:

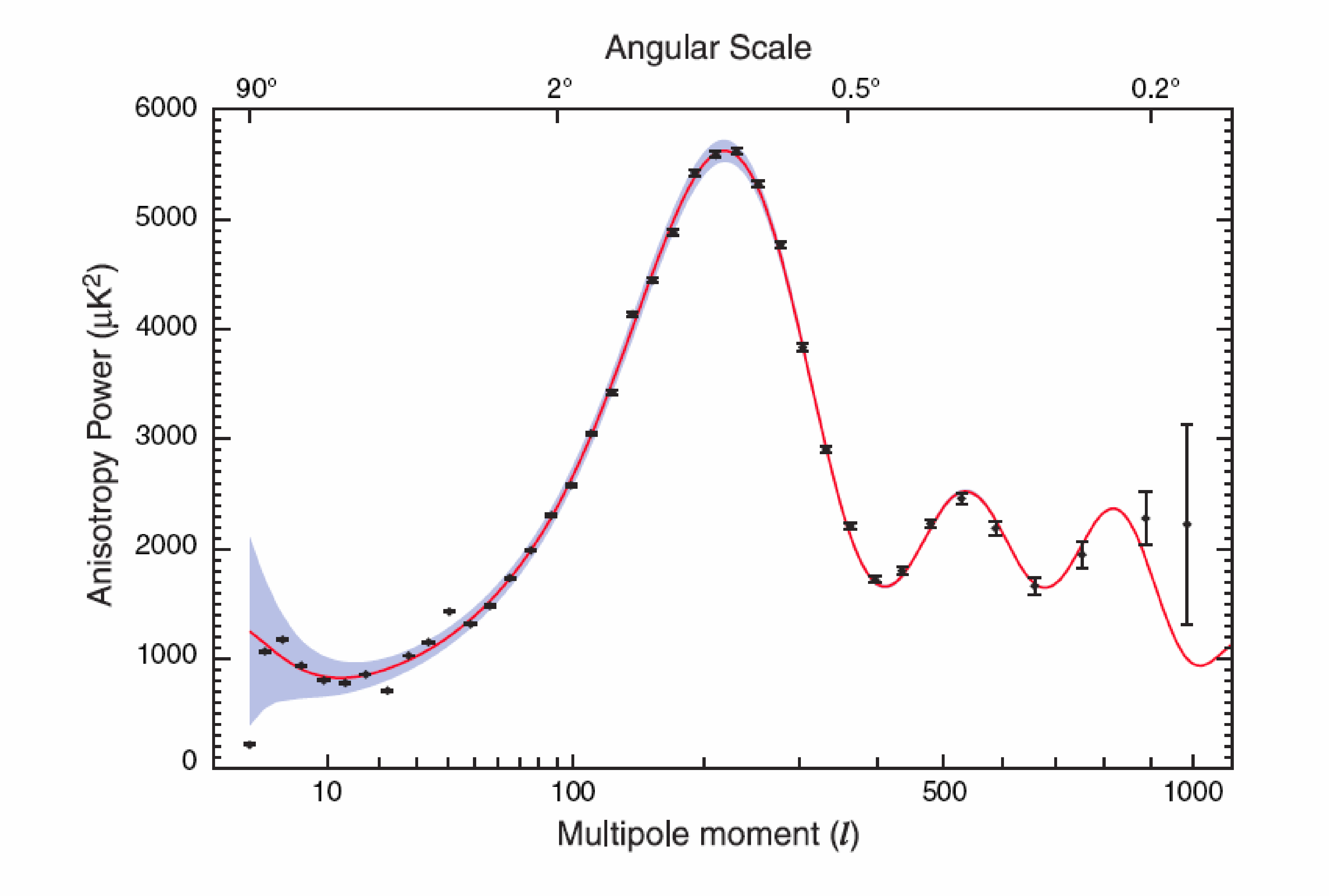
- maximum likelihood estimate of coefficients of Legendre polynomial expansion of $C(\theta)$ instead of $(2\ell+1)^{-1}\sum_m |a_{\ell m}|^2$

Quadrupole and Octopole still strange:

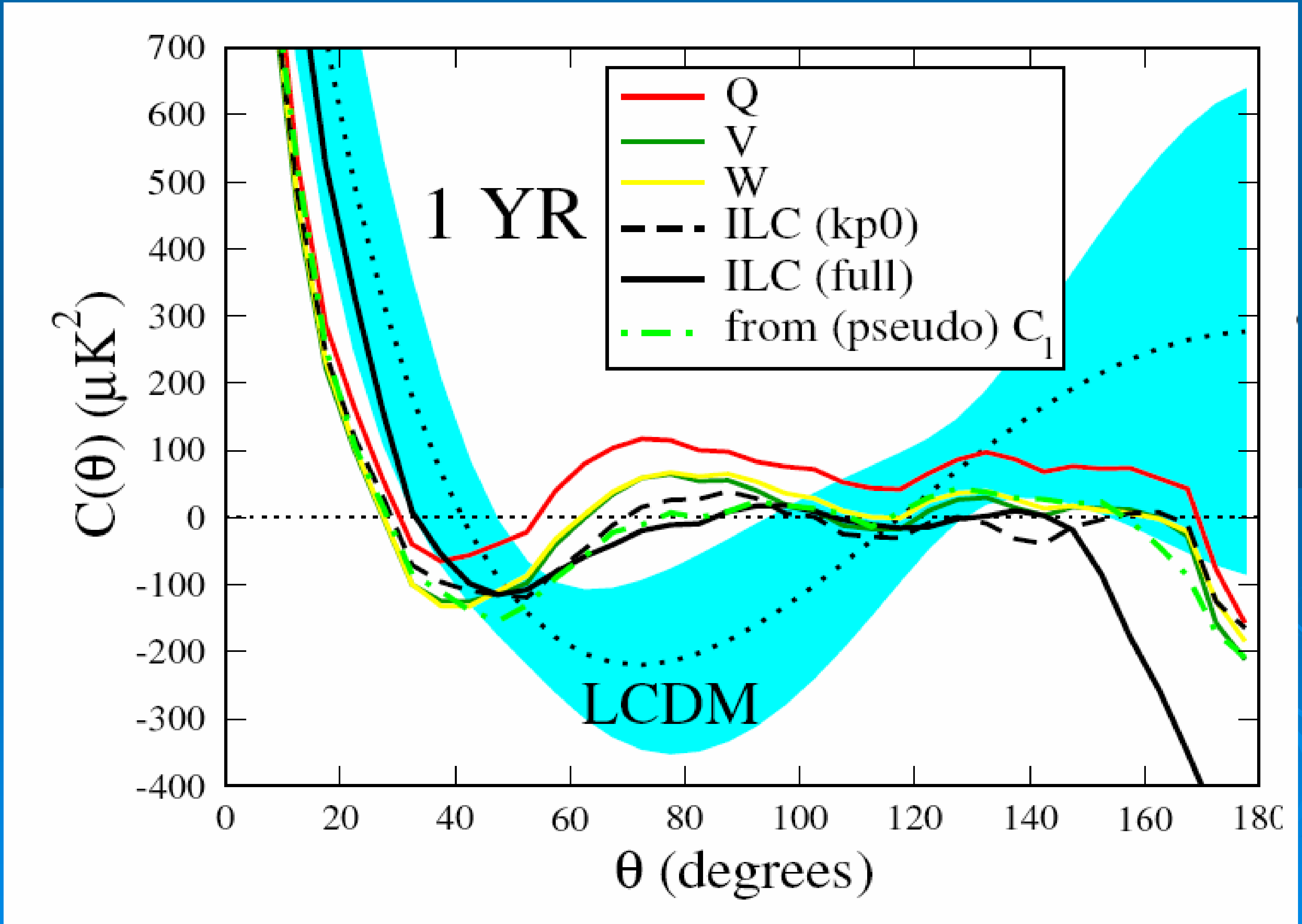
- planar (octopole)
- aligned with each other
- perpendicular to ecliptic
- normal points toward equinox/dipole
- oriented so that ecliptic separates extrema

NOT Statistically Isotropic

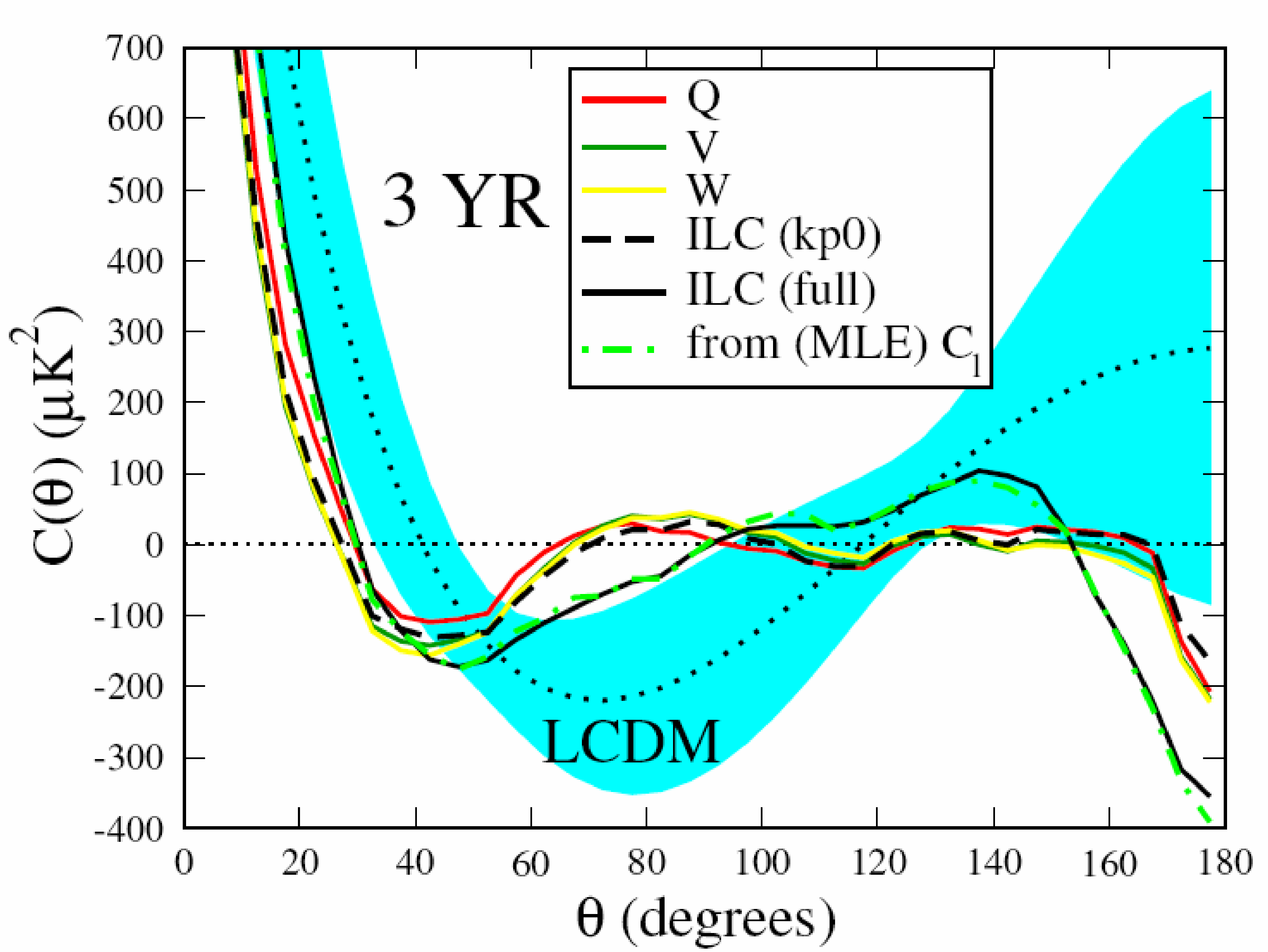
"The Low-*l* Anomaly? What Low-*l* Anomaly?"



Two point angular correlation function -- WMAP1



Two point angular correlation function -- WMAP3

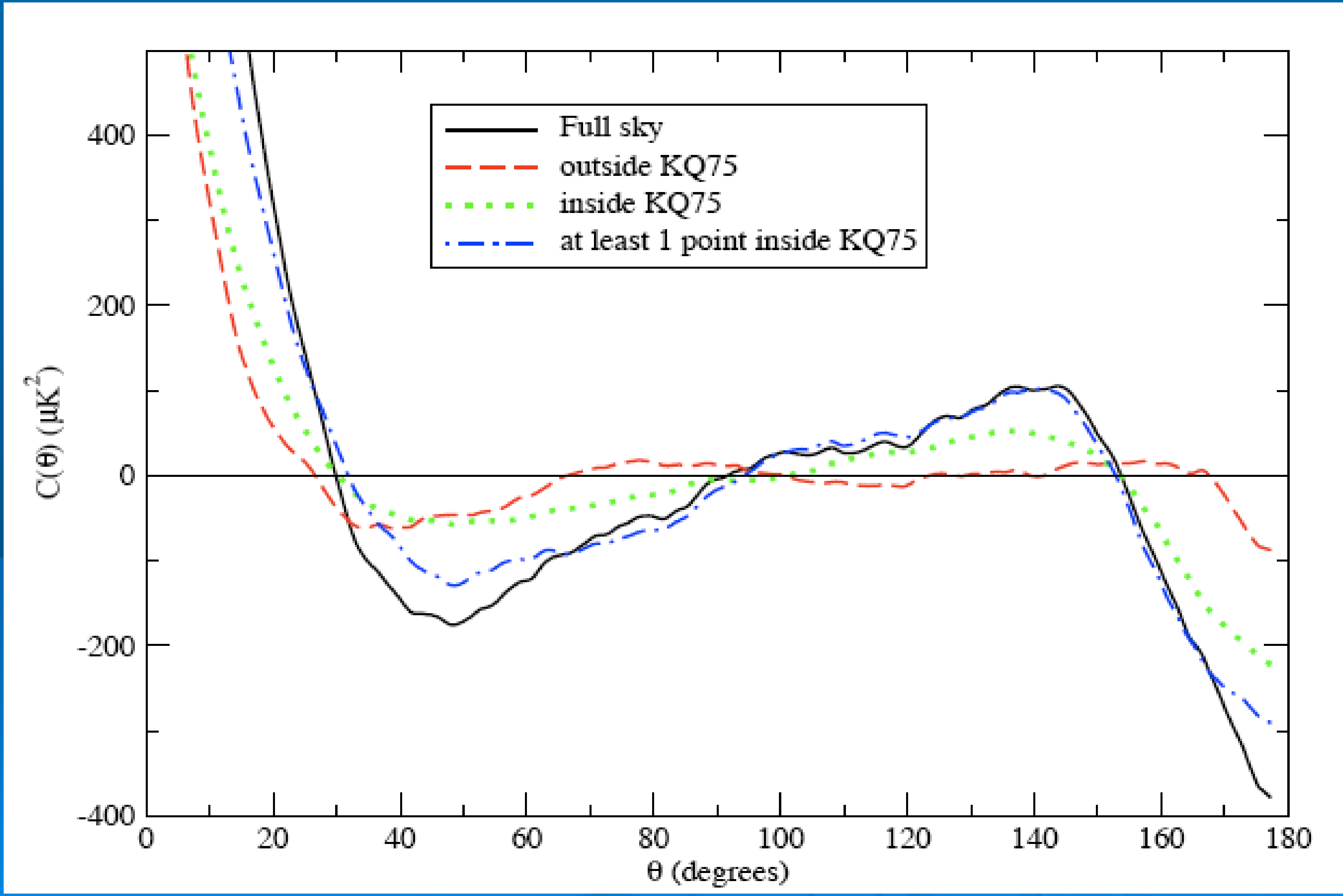


Statistics of C(θ)

Table 1. The C_ℓ calculated from $C(\theta)$ for the various data maps. The WMAP (pseudo and reported MLE) and best-fit theory C_ℓ are included for reference in the bottom five rows.

Data Source	$S_{1/2}$ $(\mu K)^4$	$P(S_{1/2})$ (per cent)	$6C_2/2\pi$ $(\mu K)^2$	$12C_3/2\pi$ $(\mu K)^2$	$20C_4/2\pi$ $(\mu K)^2$	$30C_5/2\pi$ $(\mu K)^2$
V3 (kp0, DQ)	1288	0.04	77	410	762	1254
W3 (kp0, DQ)	1322	0.04	68	450	771	1302
ILC3 (kp0, DQ)	1026	0.017	128	442	762	1180
ILC3 (kp0), $C(> 60°) = 0$	0	—	84	394	875	1135
ILC3 (full, DQ)	8413	4.9	239	1051	756	1588
V5 (KQ75)	1346	0.042	60	339	745	1248
W5 (KQ75)	1330	0.038	47	379	752	1287
V5 (KQ75, DQ)	1304	0.037	77	340	746	1249
W5 (KQ75, DQ)	1284	0.034	59	379	753	1289
ILC5 (KQ75)	1146	0.025	81	320	769	1156
ILC5 (KQ75, DQ)	1152	0.025	95	320	768	1158
ILC5 (full, DQ)	8583	5.1	253	1052	730	1590
WMAP3 pseudo-C_ℓ	2093	0.18	120	602	701	1346
WMAP3 MLE C_ℓ	8334	4.2	211	1041	731	1521
Theory3 C_ℓ	52857	43	1250	1143	1051	981
WMAP5 C_ℓ	8833	4.6	213	1039	674	1527
Theory5 C_ℓ	49096	41	1207	1114	1031	968

Origin of C(θ)

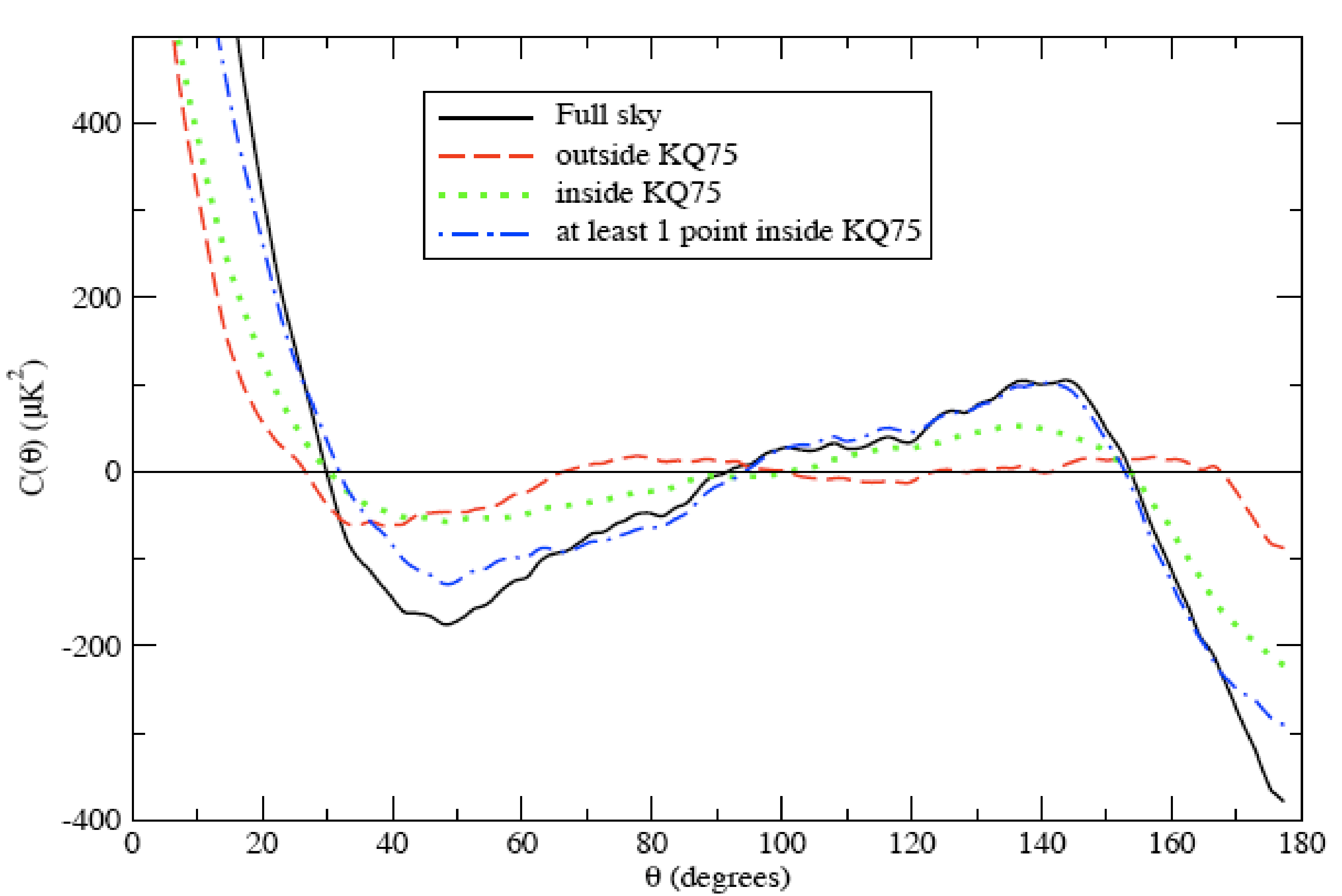


Full sky
outside KQ75
inside KQ75
at least 1 point inside KQ75
400
200
0
-200
-400
0
20
40
60
80
100
120
140
160
180
C(θ) (μK²)
θ (degrees)

Is it an accident?

Only 2% of rotated and cut full skies have this low a cut-sky $S_{1/2}$

Origin of C(θ)



Full sky
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C(θ) (μK²)
θ (degrees)

Reproducing C(θ)

Table 2. $S_{1/2}$ (in $(\mu K)^4$) obtained by minimizing with respect to C_ℓ. We show the statistic for the best-fit theory and WMAP, as a function of the cutoff multipole $\ell_{\max,\mathrm{tune}}$ (the minimization has been performed by varying all ℓ in the range $2 \leqslant \ell \leqslant \ell_{\max,\mathrm{tune}}$ and fixing $\ell > \ell_{\max,\mathrm{tune}}$). Also shown is the 95 per cent confidence region of the minimized $S_{1/2}$ derived from chain 1 of the WMAP MCMC parameter fit. In the bottom row, we remind the reader that the measured value of $S_{1/2}$ outside the cut is 1152 $(\mu K)^4$ (see Table 1 for more details).

C_ℓ	Maximum tuned multipole, $\ell_{\max,\mathrm{tune}}$						
Source	2	3	4	5	6	7	8
Theory	7624	922	118	23	7	3	0.7
Theory 95 per cent	6100–12300	750–1500	100–200	20–40	7–14	3–6	1–3
WMAP	8290	2530	2280	800	350	150	130
ILC5 (KQ75)			1152				

To obtain $S_{1/2}$<971 with the WMAP C_{l}, requires varying C_2, C_3, C_4 and C_5.

Violation of GRSI condition

Even if we replaced all the theoretical C_l by their measured values up to l=20, cosmic variance would give only a 3% chance of recovering this low an $S_{1/2}$ in a particular realization!!!

SUMMARY

- If you believe the observed full-sky CMB:

There are signs of the failure of statistical isotropy

- These are VERY statistically significant 99.9%->99.995%
- The observed low-*l* fluctuations seem to be correlated to the solar system (but not to other directions with any statistical significance)

SUMMARY

- If you don't believe the CMB inside the Galaxy cut (and you probably shouldn't) then:

- CMB shows signs of distinct lack of large angle correlations
  - this was first seen by COBE (~5% probability), but is now statistically much less likely (~.03% probability)
  - the low-ℓ C_ℓ are therefore not measuring large angle ($\theta \sim \pi / \ell$), but rather smaller angle correlations

- This lack of correlations/power could be due to:
  - Statistical fluctuation -- incredibly unlikely
  - Topology -- not (yet?) seen
  - features in the inflaton potential -- contrived, and still only a 3% chance of such low $S_{1/2}$

Conclusions

- We can't trust the low-ℓ microwave to be cosmic =>
  - inferred parameters may be suspect (τ, A, σ_8,…)
- Removal of a foreground will mean

even lower C(θ) at large angles

expect $P(S^{wmap} | \text{Standard model}) \ll 0.03\%$

Contradict predictions of generic inflationary models at >99.97% C.L.

While the cosmic orchestra may be playing the inflation symphony, somebody gave the bass and the tuba the wrong score. They're trying very hard to hush it up.

There is no good explanation for any of this.

Yet.